2003-09

A multi-year ammunition procurement model for Department of the Navy non-nuclear ordnance

Bruggeman, John H.

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/870

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A MULTI-YEAR AMMUNITION PROCUREMENT MODEL FOR DEPARTMENT OF THE NAVY NON-NUCLEAR ORDNANCE

by

John H. Bruggeman

September 2003

Thesis Advisor:	W. Matthew Carlyle
Second Reader:	Gerald G. Brown

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY	**2. REPORT DATE** September 2003	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE A Multi-Year Ammunition Procurement Model For Department Of The Navy Non-Nuclear Ordnance	**5. FUNDING NUMBERS**
6. AUTHOR (S) John H. Bruggeman	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Ammunition Logistics Center Mechanicsburg PA	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the U.S. Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE** A

13. ABSTRACT

The Navy Non-nuclear Ordnance Requirements (NNOR) assessment determines annually the preferred inventory levels for most Navy munitions. This requirement determination is unrestricted by cost. Procurement planners must then revise multi-year purchasing recommendations that satisfy current budgetary constraints (about $2 billion annually) by subjectively imposing a series of procurement priorities. This report documents the existing manual procurement planning method, expresses this method in a mathematical model that is then optimized to mimic perfect manual planning, introduces a metric for quantifying the capability provided by a given inventory of a munition, and introduces the Assessment and Investment Model (AIM) that will suggest a multi-year purchasing plan that maximizes the capability of the inventory subject to consideration of budget, industrial base, maintenance, and NNOR requirements. When initial AIM formulations could not be solved in reasonable time with commercial optimization software, a purpose-built constructive heuristic was devised to provide quick solutions. Experience with this heuristic lead to a key insight on how to help AIM solve quickly.

The Navy Ammunition Logistics Center (NALC) wants to improve the way it plans procurement recommendations. This thesis was invited by NALC and they have endorsed the metric we develop as a better quantitative assessment of inventory capability. We show that AIM procurement recommendations are superior to those of existing methods. The goal is a more combat-effective munitions inventory for any given weapon procurement budget.

14. SUBJECT TERMS Munitions Procurement, Optimization, Measure of Capability	**15. NUMBER OF PAGES** 121
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500 **Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18**

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

A MULTI-YEAR AMMUNITION PROCUREMENT MODEL FOR DEPARTMENT OF THE NAVY NON-NUCLEAR ORDNANCE

John H. Bruggeman
Major, United States Marine Corps
B.S., United States Naval Academy, 1991

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2003

Author:
John H. Bruggeman

Approved by:
W. Matthew Carlyle
Thesis Advisor

Gerald G. Brown
Second Reader

James N. Eagle
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The Navy Non-nuclear Ordnance Requirements (NNOR) assessment determines annually the preferred inventory levels for most Navy munitions. This requirement determination is unrestricted by cost. Procurement planners must then revise multi-year purchasing recommendations that satisfy current budgetary constraints (about $2 billion annually) by subjectively imposing a series of procurement priorities. This report documents the existing manual procurement planning method, expresses this method in a mathematical model that is then optimized to mimic perfect manual planning, introduces a metric for quantifying the capability provided by a given inventory of a munition, and introduces the Assessment and Investment Model (AIM) that will suggest a multi-year purchasing plan that maximizes the capability of the inventory subject to consideration of budget, industrial base, maintenance, and NNOR requirements. When initial AIM formulations could not be solved in reasonable time with commercial optimization software, a purpose-built constructive heuristic was devised to provide quick solutions. Experience with this heuristic lead to a key insight on how to help AIM solve more rapidly.

The Navy Ammunition Logistics Center (NALC) wants to improve the way it plans procurement recommendations. This thesis was invited by NALC and they have endorsed the metric we develop as a better quantitative assessment of inventory capability. We show that AIM procurement recommendations are superior to those of existing methods. The goal is a more combat-effective munitions inventory for any given weapon procurement budget.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGEMENTS

I extend my personal thanks and professional gratitude to CDR Phil Fahringer, recently at the Naval Ammunition Logistics Center (NALC). CDR Fahringer consistently provided clear guidance and thoughtful feedback along the way.

I appreciate the significant efforts of Associate Professor W. Matthew Carlyle and Distinguished Professor Gerald G. Brown. Without their assistance I would not have gotten nearly so far.

As with everything I have done, my wife, Marie, has shown endless support. Her name belongs on the cover page as much as mine.

THIS PAGE INTENTIONALLY LEFT BLANK

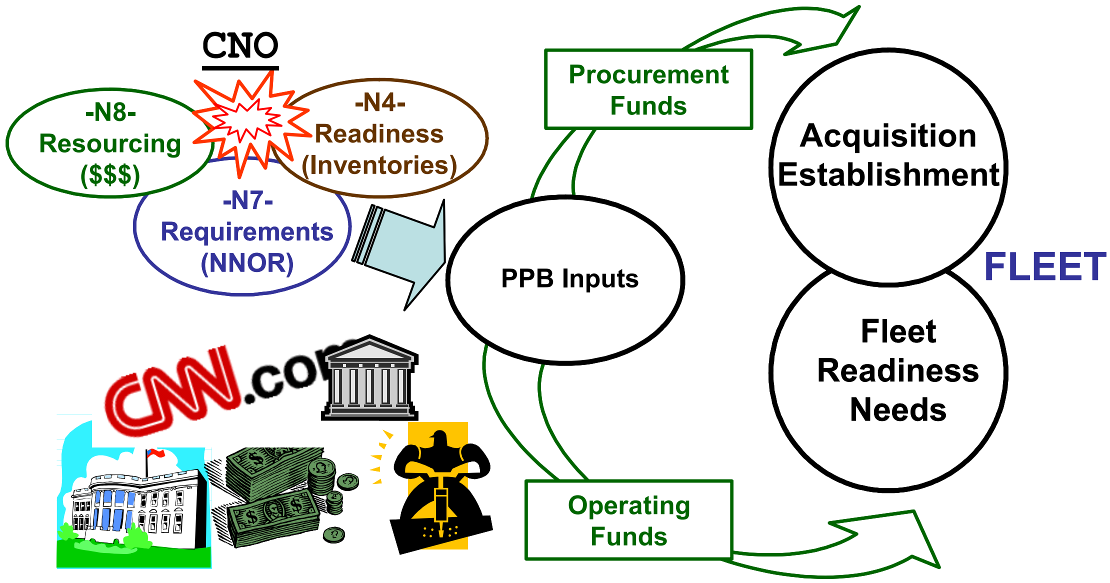
EXECUTIVE SUMMARY

U.S. Navy munition inventories often fall below 50% of the requirements revised annually by the Navy Non-nuclear Ordnance Requirements (NNOR) review. Despite annual investments of about $2 billion to replenish inventories, this deficiency has remained a chronic concern for many years. Faced with an inevitably-infeasible procurement problem, how do you best allocate available funds to maximize the effectiveness of what you can afford to buy and maintain?

Planning munitions procurements for the U.S. Navy is a complicated task with many agencies involved and a significant amount of money at stake. Currently, analysts apply a loose set of priorities to data managed in a series of spreadsheets to manually allocate budgets and make procurement recommendations. There is no objective assessment of the quality of any candidate procurement plan.

We present an objective method for assigning munition procurement priorities and a mathematical model for determining a procurement plan that optimizes this capability of the munitions inventory.

Each year, the goal of procurement planners is to provide the operating forces with an "ideal" weapons inventory that gives them the capability to accomplish all of their training goals and be fully prepared for any foreseeable combat requirements.



Munition procurement and maintenance plans that satisfy fleet munitions needs require guidance from many agencies and attract attention from outside the military, e.g., government, industry, and the media.

Determining procurement recommendations is complicated by variable munitions costs that depend on quantity discount pricing, maintenance throughput constraints, and inventory goals that are unattainable given current inventory levels, weapons costs, and munitions procurement budget allowances. This leaves procurement planners the task of determining which munitions to purchase in order to provide the most "effective" inventory possible. This is currently done through the management of a series of spreadsheets and application of some subjective procurement priorities.

Typically, unexpected expenditures from the previous year, primarily due to combat operations, are replaced first. Next, the anticipated expenditures for the current

year, primarily for training, are purchased. Then minimum production quantities are satisfied in order to maintain the industrial base for weapons production. Finally, any remaining funds are distributed to the munitions that are the furthest from their desired inventory counts or are (subjectively) considered to be the most essential to the combat effectiveness of the force. Determining this priority requires a measure of the capability of a munition based on the size of its current inventory. The metric being used now is the ratio of the current inventory count to the desired inventory count.

The current method is manual, myopic, not omniscient, and certainly not an optimal application of the rules given. We document the current planning methods and mimic them in a mathematical optimization model, called BASELINE. BASELINE suggests an annual munition procurement plan over an 8-year planning horizon that maximizes the ratio of the current inventory count to the desired inventory count.

However, this metric is too simple. It fails to account for the differences in the intended uses of munitions and the complexity of the method for determining inventory goals. We propose an alternate metric for assessment of the capability of an inventory: a weighted sum of the four component NNOR munitions requirements --- Training and Testing Requirement (TTR), Current Ops/Force Protection Requirement (CO/FPR), Combat Requirement (CR), and Strategic Reserve Requirement (SRR) --- where each weight is determined by the prioritization of a mission area for which a munition may be employed.

Three mission areas are mapped to the component NNOR requirements:

Mission Area		**NNOR Requirement**
Training	=	TTR
Force Protection	=	CO/FPR
Combat Operations	=	CR + SRR

The ability to satisfy the requirements of any single mission area with a given munition inventory is quantified in a series of ***capability scores***, each corresponding to a percentage of the appropriate NNOR requirement. We use six capability scores ('A' through 'F') with respective percentages of 100%, 70%, 60%, 50%, 40%, and 0%. The mission areas are ordered as primary, secondary, and tertiary for a given munition and the desired capability score is determined for each mission area in a logical way. The NNOR requirement mapped to each mission area is then weighted according to the capability score of that mission area.

For example, if a munition is preferred as a training round, or for combat, we express this aggregate preference and then express how well increasing inventory counts achieve this multi-criteria mission requirement: these weighted sums determine an ordinal series of inventory count threshold values, referred to as ***tier levels***, each of which represents an increase in capability score for that munition. The minimum tier level achieved by all munitions

in a given year is used to represent the overall capability of the entire inventory.

Consider a munition with a TTR of 600, CO/FPR of 1400, CR of 1000, and SRR of 800, for a Total Munition Requirement (TMR) of 3800. Assume this munition's primary mission area is training, secondary is combat operations, and tertiary is force protection. To achieve a capability score of 'B' in the primary mission area (training) and 'D' in the secondary and tertiary areas (combat operations and force protection) will require 70% of the TTR, 50% of the sum of CR and SRR, and 50% of CO/FPR;

$$.70*600 + .50*(1000+800) + .50*1400 = 2020.$$

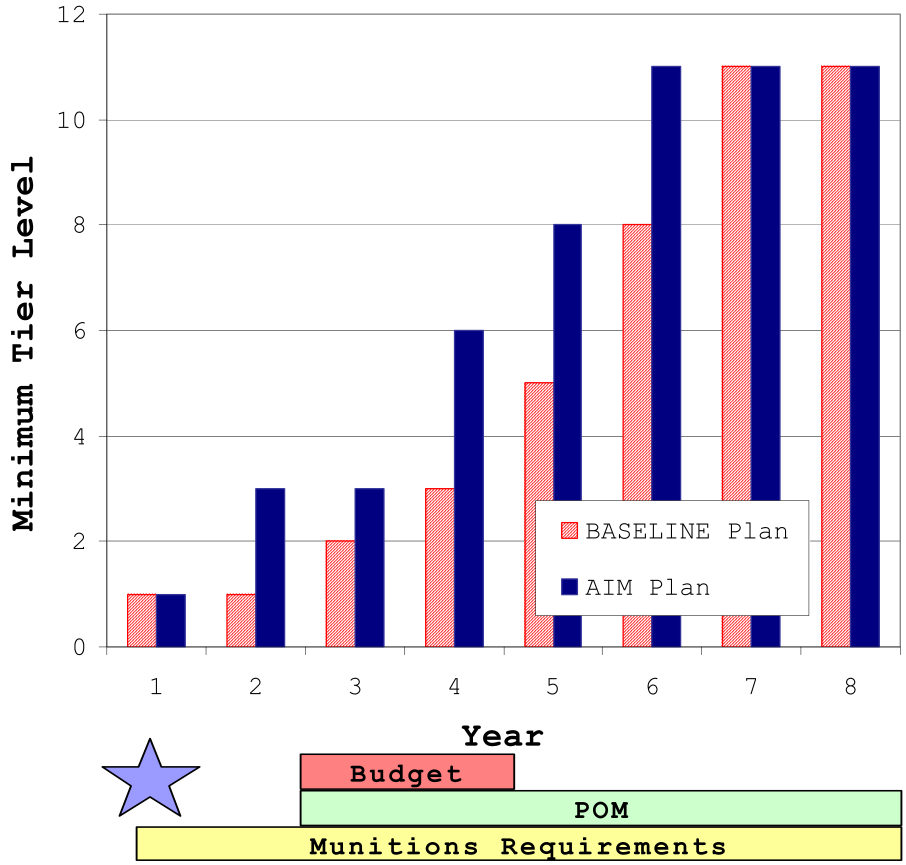
Therefore, achieving this desired tier level requires an inventory count of 2020. In our current scheme, this corresponds to tier level 9 out of a possible 16, where tier level 16 is achieved when all missions are given capability score 'A'.

These tier levels are then used in our new Assessment and Investment Model (AIM). AIM is an optimization-based procurement decision support system based on an integer linear program that suggests annual munitions procurements over an eight-year planning horizon to satisfy a variety of industrial base, maintenance effort, inventory level, and fiscal constraints, while optimizing the capability score of the entire inventory.

Initially, AIM could not complete plans in reasonable time with commercial optimization software. As an alternative, we pursued a constructive heuristic designed to employ the tier level concept and produce procurement

recommendations quickly. Analysis of this heuristic resulted in key insights on how to help optimization software solve AIM much more rapidly.

In comparison with procurement recommendations generated by the BASELINE model, an emulation of current practice but with maximal effectiveness, AIM offers superior plans; AIM achieves a larger total inventory and, more importantly, AIM raises the overall inventory capability level more quickly during the key intervening years of the eight-year planning horizon.



A comparison of an AIM plan to a BASELINE plan illustrates the difference in overall capability of the inventory (measured by Minimum Tier Level, that of the munitions in the worst shape). Use of AIM in the planning, programming, and budgeting process can provide significantly improved capability in the critical years of the planning horizon.

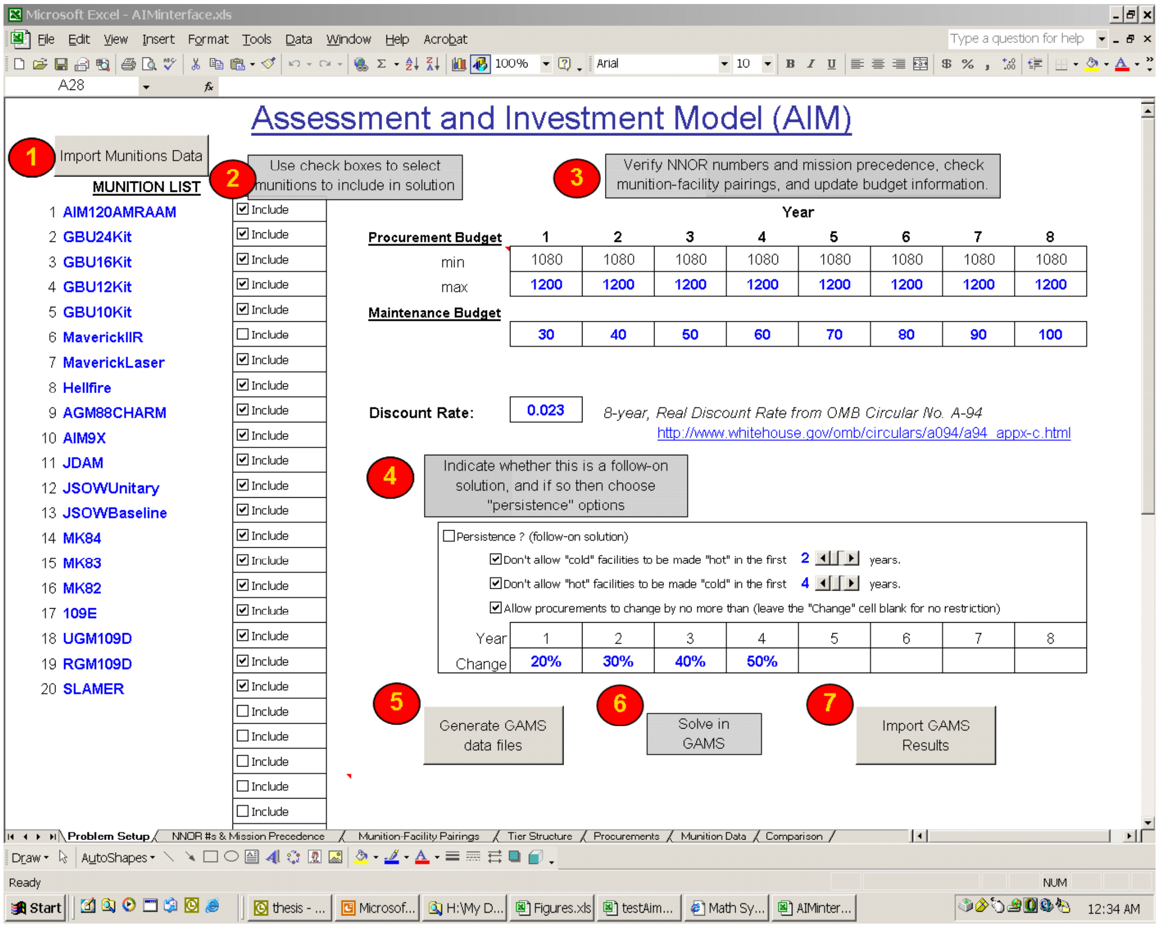
AIM is an effective tool for managing munitions procurement and generating multi-year procurement recommendations by placing priority on munitions whose inventory counts result in low capability scores and by maximizing the budget available to increase the overall combat effectiveness of the inventory.

JDAM	**procurements**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**
	maint performed	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**
	delivered	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
	maint due	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
	expended	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
	maint invent (EOY)	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
	active invent (EOY)	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**	**xxxx**
	tier level	2	5	6	8	8	8	11	11
	consolidated cost	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx

The AIM-recommended procurement plan invests in munitions with lowest tier levels (a measure of the weakest capability in our inventory). The budget allocation maximizes the minimum achievable tier level. "xxxx" entries obscure classified data.

The ability to provide objective justification to rationalize procurement recommendations should appeal to munitions procurement planners who currently struggle to satisfy a variety of agencies, each with distinct conflicting priorities.

AIM also has the ability to limit changes to a legacy solution in order to conduct basic sensitivity analysis or "what-if" excursions. To facilitate the use of AIM, all data management and parameter-setting is accomplished through a spreadsheet interface that speeds problem set-up. This interface also displays AIM procurement recommendations and provides for quick analysis.



The AIM spreadsheet interface provides push-button support for importing munition data, setting parameters, selecting options, and viewing results. Button #1 imports munition data directly from existing files. At #2 the planner can choose to generate a plan for any subset of all available munitions. The table at #3 allows the planner to provide budget information. The set of options at #4 provide the ability to limit changes to a legacy solution. Button #5 exports the data and parameter settings to appropriately formatted files used by AIM. After generating a procurement plan (#6), the plan can be imported back into the interface for display and analysis with button #7.

The use of AIM can streamline planning munitions procurement recommendations and result in a significant

improvement to the combat effectiveness of our munitions inventory.

The Naval Ammunition Logistics Center (NALC) has been instrumental in guiding the development of AIM, and has informed us they want to try AIM this fall.

I. INTRODUCTION

A. THE MUNITION PROCUREMENT PROBLEM

Each year, procurement planners in the Department of the Navy must decide how to allocate nearly two billion dollars to purchase munitions [DoN, 2003]. Their goal is to provide operating forces with an "ideal" weapons inventory, thereby allowing the Navy to accomplish all of its training goals and be fully prepared for any combat requirements. ***The problem is that current inventory counts often fall below 50% of these "ideal" inventory counts.*** Despite such a significant budget, in recent years it has been difficult to make any progress toward reaching the desired inventory counts. As a result, the operating forces of the Navy must accomplish both training and operational missions with inadequate munitions resources. In fact, a recent Government Accounting Office report cited "shortages of training ordnance as a contributing factor to low initial air wing success in the delivery of precision ordnance" [GAO, 2001].

Munitions procurement planning currently allocates money according to a set of priorities. Unexpected expenditures from the previous year, primarily due to combat operations, are replaced first. Next, the anticipated expenditures for the current year, primarily for training, are purchased. Then minimum production quantities are satisfied in order to maintain the industrial base for weapons production. Finally, any remaining funds are distributed to the munitions that are the furthest from their desired inventory counts or are

(subjectively) considered to be the most essential to the combat effectiveness of the force [Fahringer, 2002]. This is further complicated by variable munitions procurement costs that depend on quantity discount pricing, maintenance throughput constraints, and inventory goals that are unattainable given current inventory levels, weapons costs, and munitions procurement budget allowances. This leaves procurement planners the task of determining which munitions to purchase in order to provide the most "effective" inventory possible. This is done through the management of a series of spreadsheets. ***The current method is manual, myopic, not omniscient, and certainly not an optimal application of the rules given.***

We have developed a tier-based scheme for quantifying munitions inventory capability based on mission priorities and target inventories. With this assessment of capability in hand, we have also developed a procurement decision-support tool, the Assessment and Investment Model (AIM) that will generate a multi-year munitions procurement recommendation to provide the most-capable inventory achievable while satisfying a variety of financial, maintenance, and industrial base constraints. This effort has been supported by the Naval Ammunition Logistics Center (NALC), a U.S. Navy organization that is interested in this tool as a component of a larger effort to improve current logistical planning and to continue the transition to capability-based operational and logistical decision-making.

Initial results show that AIM procurement recommendations are superior to those generated by current

practice, and that they will result in a more combat-effective munitions inventory for any given (and, currently, almost $2 billion) Department of the Navy weapon procurement budget.

B. DETERMINATION OF REQUIREMENTS

1. Capabilities Based Munitions Requirements (CBMR)

The Capabilities-Based Munitions Requirements (CBMR) Process detailed in Department of Defense Instruction 3000.4 (DoDInst 3000.4) outlines the way military departments should determine their annual munitions requirements. In particular, this instruction requires each service to determine requirements, by munition, in four individual categories: the Training and Testing Requirement (TTR), the Current Operation/Forward Presence Requirements (CO/FPR), the Strategic Readiness Requirement (SRR), and the Combat Requirement (CR). The sum of these four component requirements is a munition's Total Munitions Requirement (TMR) [DoDInst 3000.4, 2001].

The CBMR instruction provides further guidance on the generation of these four individual requirements. The TTR is defined as the number of munitions required for training the force and supporting service programs that ensure that weapons and platforms deliver the intended effectiveness. The CO/FPR consists of the sum of the munitions required to arm forces to conduct current operations and those required to meet forward presence obligations according to the Defense Planning Guidance (DPG) as published in the most recent Secretary of Defense Memorandum on Defense Planning Guidance. The SRR is the quantity of munitions needed to

arm forces not committed to support combat operations in the assigned Major Theater Wars (MTWs), as well as those in the strategic reserve. The SRR also includes any additional munitions requirements accrued from treaties with allied nations. To determine the CR, each warfighting combatant commander allocates targets to each service based on warfighting combatant commander-developed Operational Plans (OPLAN) or Contingency Plans (CONPLAN) to support the current DPG. The CR is the quantity of munitions required to equip a specified force to its desired military capability in order to meet warfighting combatant commander objectives [DoDInst 3000.4, 2001].

2. Navy Non-nuclear Ordnance Requirements (NNOR)

Established by Chief of Naval Operations Instruction 8011.9A (OpNavInst 8011.9A), the Navy Non-nuclear Ordnance Requirements (NNOR) process estimates the official Department of the Navy (DoN) ordnance requirements used for Program Objective Memorandum (POM) and budget development in accordance with the DoD capabilities-based munitions requirements guidelines.

The NNOR working group meets annually to revise and establish munitions requirements for a ten-year time horizon. Three of the individual CBMR munitions requirements are determined with significant input from the Navy's Atlantic and Pacific Fleet staffs. The annual Current Operations/Force Protection Requirement (CO/FPR) is determined from the current munitions load for deploying Navy ships and the annual deployment rate of such battle groups. The Strategic Reserve Requirement (SRR) is

similarly-computed based on the current munitions loads for a variety of Navy ships in a manner consistent with the CBMR definition of the Strategic Reserve Requirement. The Training and Testing Requirement is computed directly from requests from the fleet [Fahringer, 2002].

In order to determine the fourth requirement, the Combat Requirement (CR), NNOR employs a family of computer models that is owned and operated by the Chief of Naval Operations Office for Warfare Integration, OPNAV N70. These models feature both threat and level of effort modeling and are based on the warfighting combatant commanders' OPLANS or CONPLANS, and are derived from the current DPG. The munitions requirements generated are those necessary to accomplish the destruction of the entire warfighting combatant commander-assigned Department of the Navy target allocation based on a combination of attrition and effectiveness metrics [OpNavInst 8011.9A, 1989].

The NNOR Total Munitions Requirement (TMR) is the sum of these four components (commonly referred to as the "NNOR requirements"). Three of the four individual requirements are based on current deployment practices, platform capabilities, or fleet requests, but the Combat Requirement (CR) is a result of modeling the Navy and Marine Corps' role in supporting the conflicts anticipated by the most current DPG. *NNOR is fiscally unconstrained*; these Total Munitions Requirements represent an "ideal" DoN-wide inventory to support all requirements, up to and including full-scale war.

C. OTHER PROCUREMENT FACTORS

Of course, the procurement budget places the first restriction on the acquisition process. In addition, planners must also consider other constraints to the procurement plan, including industrial base requirements and maintenance concerns.

Support of the munitions manufacturing industrial base is a high priority. Many munition components are produced by a single civilian source. Maintaining a consistent demand for these components may be critical to the financial stability of the manufacturer and is often as much of a political concern as a military one. In these cases, procurement recommendations may be required to meet some Minimum Sustaining Rate (MSR) for production, regardless of actual demand, in order to ensure the long-term availability of the munition.

Similarly, the Navy employs both military facilities and civilian contractors for the scheduled maintenance of some munitions. A consistent flow of maintenance work is more cost effective for the Navy both in its own workspaces and with outsourced work. In this regard, particularly for munitions with regularly-scheduled maintenance requirements, consistent annual procurements will translate into consistent annual maintenance, and will result in lower annual scheduled maintenance costs [Fahringer, 2002].

Finally, as with most products, the unit cost of many munitions generally decreases as the quantity procured increases. This quantity discount pricing provides an opportunity to effectively increase the buying power of the budget; however the degree to which this can be exploited

is often limited by other requirements and constraints on procurement and on maintenance capabilities.

The challenge faced by munitions procurement planners is to determine the appropriate number of munitions to procure each year. The restrictions they must consider include a limited budget, a desire to support the industrial base, regular maintenance requirements, and variable munitions costs. Their goal is to make available a munitions inventory that provides the greatest combat capability.

THIS PAGE INTENTIONALLY LEFT BLANK

II. MEASURE OF MUNITION CAPABILITY

A. CURRENT PRACTICE

The primary metric currently used by the Navy to determine munitions procurement recommendations is the inventory count of that munition as a proportion of its NNOR Total Munition Requirement (TMR). This proportion is a surrogate for a measure of the overall capability provided by a given quantity of munitions. A munition whose current inventory-to-TMR ratio is lowest will generally receive a greater share of the procurement budget in an effort to improve its capability score to a level more consistent with other munitions. While there are additional subjective influences on procurement allocation, this ratio provides the basis for procurement decision-making [Fahringer, 2002].

Using this metric as a measure of capability tacitly assumes that a given increase in the relative inventory of any two munitions, from the same initial relative inventory, generates an equivalent increase in capability. In other words, a procurement that raises the inventory of Munition A from 35% to 40% of its TMR will produce the exact same increase in capability as a procurement that raises the inventory of Munition B from 35% to 40% of its TMR, even though these weapons may have completely different purposes and performance characteristics. This metric assumes that the relationship between capability and relative inventory will be identical for every munition. As the total munition requirement is a simple sum of the four component NNOR requirements, this effectively results

in an assumption that each of the four NNOR requirements is equally important for every munition – in reality, this is clearly not the case. For example, there are weapons that are no longer preferred for combat because they have been replaced by more accurate, more lethal, or more reliable ones, but which are still in demand for training. Similarly, some weapons are preferred for full-scale, high-intensity combat while they are less likely to be used for low-intensity, or force protection roles. The current metric fails to account for this.

B. AIM MEASURES OF CAPABILITY

For the Assessment and Investment Model (AIM) we provide a unique function for each munition to relate capability score and inventory count. This function expresses varying marginal utility and mission precedence of each munition. These measures of capability will then be used to determine procurement priorities.

1. Variable Marginal Utility

From economic theory, utility is "a measure of the satisfaction gained from the consumption of an item" and marginal utility is "the additional utility (satisfaction or benefit) that a consumer derives from an additional unit of a commodity or service" [Wikipedia, 2003]. Considered from a different perspective, "marginal utility obviously corresponds to the maximum effort which one will be willing to make ... in order to obtain a further unit of that commodity" [Page, 1968, p.232]. Variable marginal utility is the additional "satisfaction" gained from each

additional unit above the number of items already owned. So, the cost which one should be willing to pay to purchase an additional item should be proportional to the variable marginal utility.

Applied to munitions, consider the requirement for a given quantity of munitions with which to conduct an activity or a mission (say, training). If a military unit determines that it requires ten munitions to make a training exercise worthwhile, and its current on-hand inventory is only two, then the addition of a single munition may not significantly increase the overall training value of the inventory. In this case, the marginal utility of a single additional munition would be low.

Similarly, when on-hand inventory approaches the total number required to accomplish all training, then each new munition may not represent a significant increase in training value. In particular, when annual training requirements are generated, they are often intentionally optimistic, planning to take advantage of every possible training opportunity and using a generous amount of munitions in each event to maximize the training potential for a military unit. In reality, not every training event occurs (e.g. cancellations due to weather, maintenance problems, scheduling, or conflicts with other events are common), and even in those that do, the planned number of munitions is not always expended. Therefore, even with less than the "required" training allowance of munitions, a unit will often accomplish as much training as can realistically be had. So, when the quantity of munitions

already on-hand is near the required amount for that mission, the additional value, or utility, provided by each additional munition is reduced.

Taken together, these concepts of variable marginal utility at the extremes of an on-hand inventory count result in a description of a total mission-related utility that increases slowly, then more rapidly, then again slowly as the size of the inventory increases from zero to the desired quantity. In this sense, a munition's utility represents the capability to accomplish a single mission provided a given munition inventory. Graphically, this relationship is depicted in Figure 1.

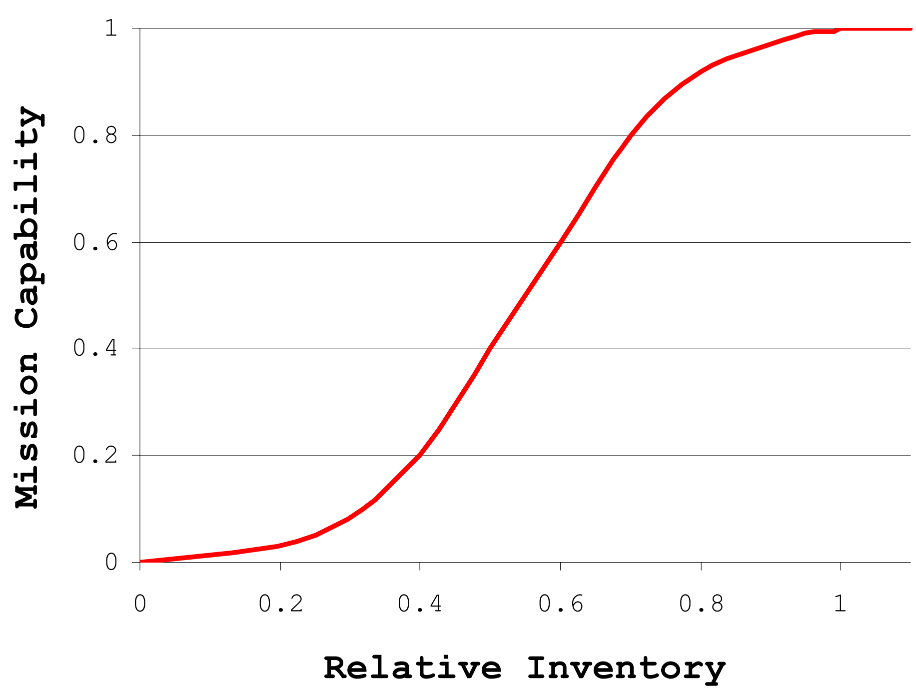


Figure 1. Mission Capability Score as a Function of Inventory Count

A typical relationship between the mission-related capability score of a munition and the inventory count as a proportion of TMR illustrates reduced marginal utility at the extreme inventory levels.

2. Overall Munition Capability

To determine the overall capability associated with a munition inventory, we must consider that in NNOR, four component munition requirements determine the total desired inventory. Just as the principle of variable marginal utility could be applied to the Training and Testing Requirement (TTR) above, it can similarly be applied to the Current Operations/Force Protection Requirement (CO/FPR), the Combat Requirement (CR), and the Strategic Reserve Requirement (SRR), in each case generating a similarly-shaped relationship between mission capability and inventory level.

a. Mission Precedence

To consolidate these four functions into one measure of overall munition capability, we first determine a technique for assigning weightings to the four component requirements. Consider three mission areas: training, force protection, and combat operations. Training is associated with the TTR. Force protection is associated with the CO/FPR. Combat operations is associated with the sum of the CR and the SRR. Each munition needs to be evaluated based on its contribution to these mission areas; the mission areas are then assigned to primary, secondary, and tertiary "mission precedence" for each munition.

The US Navy is required to maintain an allowance of weapons in order to satisfy treaty agreements with allies. This quantity of munitions is included in the SRR requirement and, for purposes of these mission area

requirements, the treaty requirement will be subtracted out of the SRR quantity to be treated separately. Therefore, the mission areas are defined as follows:

Training = TTR

Force Protection = CO/FPR

Combat Operations = CR + SRR – Treaty Requirement

b. Mission Capability Levels

Within each mission area, the mission capability function can be represented by a series of discrete jumps occurring at designated relative inventory proportions. These inventory proportions are designed to capture the general region of the current munition inventory count and the steepest portion of a "capability-to-inventory" curve. These capability levels and their associated relative inventories are given in Table 1. This relationship is depicted graphically in Figure 2.

Mission Capability Score	**Inventory (as a % of Mission Requirement)**
Level F (None)	0%
Level E (Basic)	40%
Level D (Intermediate)	50%
Level C (Advanced)	60%
Level B (Superior)	70%
Level A (Full)	100%

Table 1. Mission Capability Scores
The capability provided by a munition inventory is represented by a series of discrete jumps in relative inventory count.

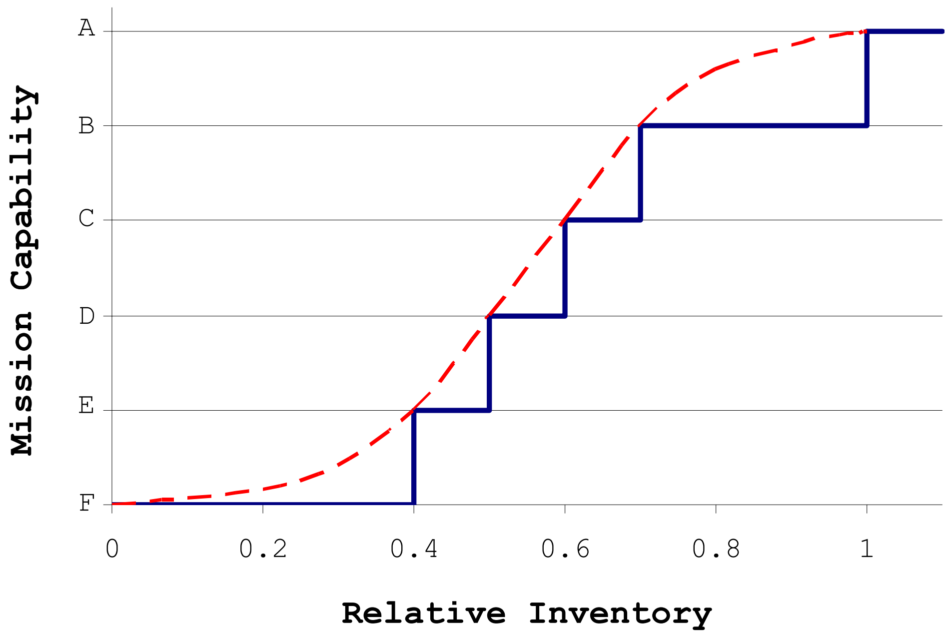


Figure 2. "Capability-to-Inventory" Curve for a Mission Area
The discrete jumps capture the steepest portion of the "capability-to-inventory" curve - representing the greatest improvement in capability per unit growth in inventory count.

With this metric, the capability of a munition to satisfy any of three assigned missions (training, force protection, and combat operations) can be categorized into one of six descriptive scores (from F, no capability, to A, full capability) based on the quantity of that munition available relative to the associated NNOR requirement.

c. Capability Tier Levels

The increasing levels of overall capability are referred to as capability tiers. With a mapping of NNOR requirements to mission areas and the descriptive capability levels with associated relative inventories, we now simply have to apply the inventory percentages to the

NNOR requirements in a manner consistent with a "mission area precedence" and sum to find the total inventory required to achieve a given overall capability. As indicated earlier, any treaty requirements will be separated from the SRR requirement and will be maintained to the full capability (satisfying 100% of the treaty requirement) at all times. The pattern for computing the quantity of munitions required to achieve any tier level is shown in Table 2. While this guide is somewhat arbitrary, it represents a reasonable progression through the mission capability scores.

Tier Level	**Mission Areas**			**Treaty Requirement**
	Primary	**Secondary**	**Tertiary**	
1	F	F	F	A
2	E	F	F	A
3	D	F	F	A
4	D	E	F	A
5	D	E	E	A
6	C	E	E	A
7	C	D	E	A
8	C	D	D	A
9	B	D	D	A
10	B	C	D	A
11	B	C	C	A
12	A	C	C	A
13	A	B	C	A
14	A	B	B	A
15	A	A	B	A
16	A	A	A	A

Table 2. Tier Level Formulation
Progression through the capability scores is led by the primary mission area; secondary and tertiary mission areas follow at least one capability score behind.

d. Example Tier Level Computation

As an example, consider two fictional munitions with the NNOR requirements and mission area precedence as shown in Table 3.

	Munition A	**Munition B**
NNOR Requirements		
TTR	600	100
CO/FPR	1400	50
CR	1000	600
SRR	800	700
TMR	3800	1450
Treaty Requirement	0	100
Mission Precedence		
Primary	Training	Combat Ops
Secondary	Combat Ops	Training
Tertiary	Force Protection	Force Protection

Table 3. Fictional Munition Requirements and Mission Precedence
Munition A may be a low technology, general-purpose weapon heavily used in training. Munition B may be a more advanced weapon preferred for specific targets in combat.

To compute the tier 9 inventory requirement for Munition A, note from Table 2 that tier 9 requires a capability level of B in the primary mission area, D in the secondary and tertiary mission areas, and A for a treaty requirement if one exists. Therefore, applying the capability level inventory percentages from Table 1:

tier 9 inventory level (munition A) =

$$.70*600 + .50*(1000+800) + .50*1400 + 1*0 = 2020.$$

Thus, to achieve the overall capability represented by tier level 9, munition A must reach just

over 53% of its TMR of 3800. Performing a similar computation for tier 9 of munition B:

tier 9 inventory level (munition B)=

$$.70*(600+700-100) + .50*100 + .50*50 + 1*100 = 1015.$$

We see here that munition B must achieve 70% of its TMR of 1550 to provide the same level of overall capability.

Figure 3 graphically depicts the complete tier level-to-relative inventory count relationships for the fictional munitions from this example. Note that an increase in inventory count from 60% to 72% for munition A increases its overall capability by only three tier levels while a similar increase in inventory count for munition B raises its capability by six tier levels. Also note that munition A achieves tier level 15 with a relative inventory count of 89% of TMR, meanwhile munition B has significantly less overall capability (tier level 11) with nearly 95% of its TMR.

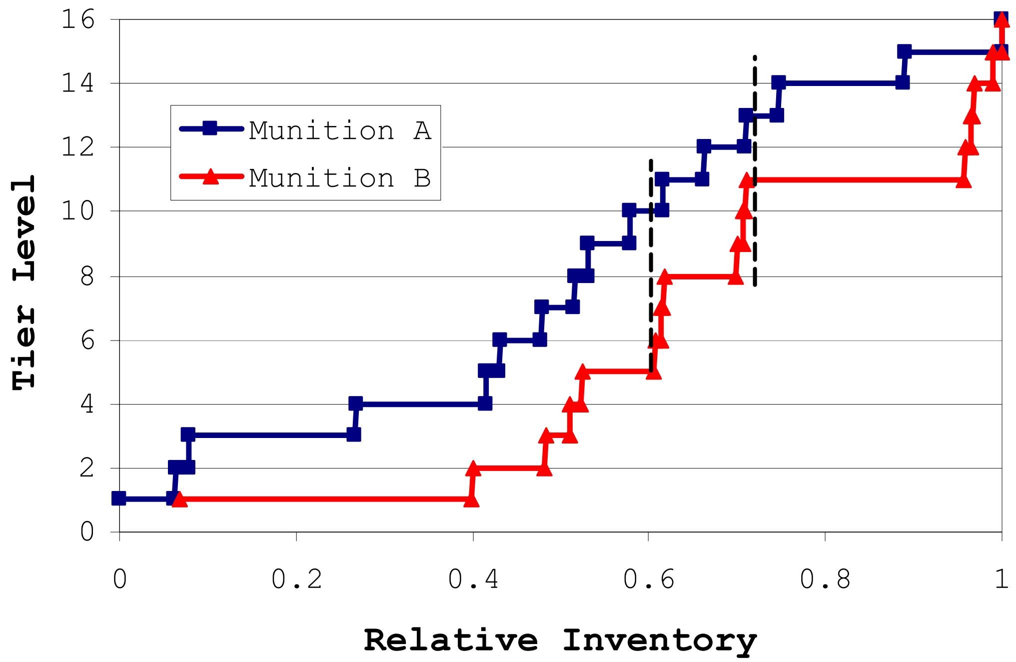


Figure 3. Comparison of Munition A and Munition B Tier Levels
Significant differences are possible between two munition-specific tier level functions. Note that when the Munition A inventory count is 60% of its Total Munition Requirement (TMR) it is in tier level 10. When the Munition B inventory count is also at 60% of TMR it is only in tier level 5.

This computation incorporates the principle of declining marginal utility and varying importance of the distinct NNOR requirements, generating a munition-unique relationship between relative inventory count and munition capability. Each munition will have its own curve, mapping inventory levels to capability tiers, and the shape of these curves will dictate how munitions capability trade-offs are made in the presence of restrictions. This metric offers a precisely-characterized and rational assessment of the capability of a munition inventory accounting for

component NNOR requirements and the variety of potential uses of a munition.

III. ASSESSMENT AND INVESTMENT MODEL (AIM)

A. OVERVIEW

The Assessment and Investment Model (AIM) is an integer linear program that prescribes annual munitions procurements over a fixed (eight year) planning horizon in order to maximize munition inventory capability while satisfying a variety of financial, maintenance, and industrial base constraints. AIM is written in the General Algebraic Modeling System (GAMS) language [Brook, Kendrick, Meeraus, and Raman, 1998]. As input, AIM requires a significant amount of individual munition data, budget projections for each year in the planning horizon, and the munition tier levels. The output includes recommended procurement and maintenance schedules for the eight-year time horizon as well as visibility of penalties encountered due to violations of so-called “elastic” constraints. To facilitate the use of AIM, all data management and parameter-setting is accomplished through a spreadsheet interface that speeds problem set-up. This interface also displays AIM procurement recommendations and provides for quick analysis.

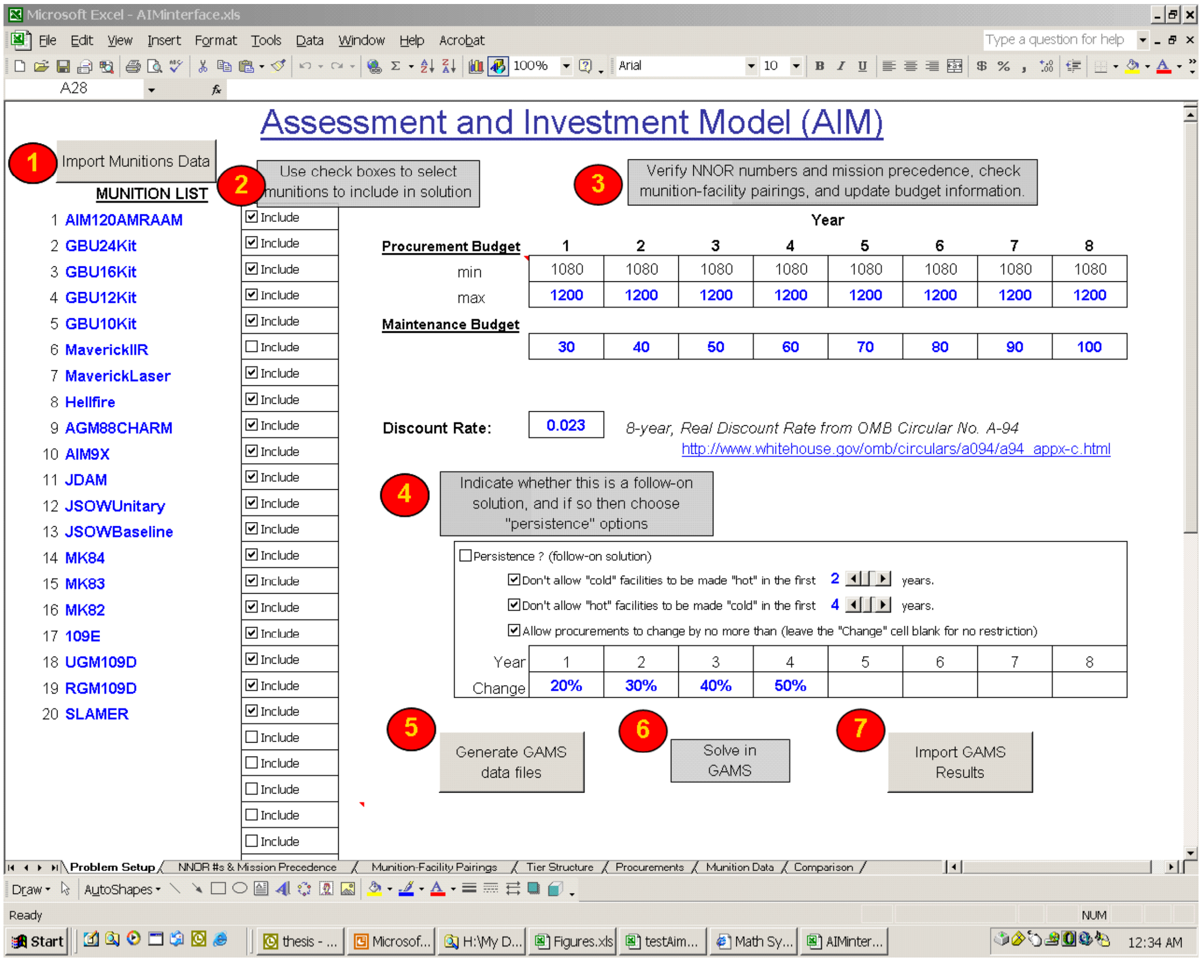


Figure 4. AIM Spreadsheet Interface

The AIM spreadsheet interface automates the process of importing and preparing data. Button #1 imports munition data directly from existing files. At #2 the planner can choose to generate a plan for any subset of all available munitions. The table at #3 allows the planner to provide budget information. The set of options at #4 provide the ability to limit changes to a legacy solution. Button #5 exports the data and parameter settings to appropriately formatted files used by AIM. After generating a procurement plan (#6), the plan can be imported back into the interface for display and analysis with button #7.

B. INVENTORY ACCOUNTING AND MAINTENANCE REQUIREMENTS

AIM uses year-end inventories. For each munition, data requirements include the size of the initial

inventory, previously-scheduled or contracted procurements (by year in which the munitions will be accepted into inventory), and planned expenditures. The number of combat-useable munitions that are present at the end of each year is referred to as the active inventory count achieved for that year.

Some munitions require regularly-scheduled preventive maintenance. This maintenance is intended to routinely detect and correct mechanical and electrical problems in munitions that have not been expended after a given active-service epoch. When a munition that requires scheduled maintenance reaches its maintenance deadline, it is removed from the active inventory and placed in the maintenance inventory. When the required maintenance is begun the munition is removed from the maintenance inventory. A munition can begin maintenance in the same year it reaches its maintenance deadline. When the maintenance of a munition is complete, it is returned to the active inventory. The length of time (in years) for required maintenance to be completed is given for each munition. The next scheduled maintenance for a munition is based on the year that it re-enters the active inventory.

C. PROCUREMENT PRIORITIZATION

For each munition, the NNOR requirements are pre-processed to generate a series of increasing tier levels. In previous examples, these have been a sixteen-tier structure. In AIM, the tier structure can be adjusted to accommodate any number of tiers and any progression through mission capability levels. Simplifying the tier structure

significantly reduces the intellectual and computational complexity of the problem and may be desirable in some cases.

In any tier structure, the lower bound of Tier 1 must represent the minimum inventory allowable (in most cases, either zero or the treaty requirement). The upper bound of every tier (except the last) is determined to be one munition short of the next tier's lower bound. The highest tier will have a range of only a single munition and this will equal the exact NNOR Total Munition Requirement.

The annual capability of a munition, measured by the tier level achieved by the end of that year, is determined by the active inventory for that munition. The objective function in AIM is primarily composed of the minimum tier achieved over all munitions in each year; therefore there is a significant incentive to increase this minimum tier level by raising the inventory count of munitions with low tier levels. This can be done, in the case of every munition, through procurement of new munitions, and, in the case of the munitions that require regular maintenance, by conducting maintenance on those items in the maintenance inventory. When new munitions are procured they enter the active inventory after some prescribed delay (given for each munition in years).

D. INDUSTRIAL BASE CONSTRAINTS AND MUNITION 'FAMILIES'

The industrial base is modeled using two values for each munition, the Minimum Sustaining Rate (MSR) and the Maximum Production Rate (MPR). The MSR represents the minimum annual quantity of new munitions procurement

required to support a production process. The MPR describes the maximum annual quantity of new procurement that can be supported without significant upgrades to the production process. Both of these constraints are elastic, and violations of the industrial base constraints are penalized at different rates for under- and over-production.

Annual munition procurement is semi-continuous. In each year, the total annual procurement must be equal to or greater than the MSR, or it must be zero. Failure to support the MSR is penalized with a fixed cost penalty applied to the procurement budget in that year - representing the cost to the Navy of maintaining the capability of the production line in order to make future production of the munition possible. Penalty costs do not increase in the case of multiple consecutive years of non-production, nor is there an additional, explicit 'start-up' cost when production resumes, as this cost is assumed in the penalty cost already paid.

Violations of Maximum Production Rate (overproduction) are penalized by a proportionate increase to the unit cost for each munition above MPR - representing the additional cost per munition to expand production capability. This additional cost can reasonably be assumed to represent mostly overtime wages for increasing the overall production time required; however, in extreme cases it may also represent the costs of additional machinery, parts, workforce, or even facilities. The penalty proportion is a global parameter and every munition suffers a similar relative penalty for overproduction.

Some munitions are simply different variants of the same base weapon. Examples of this include the many variants of the Tomahawk cruise missile and the several variants of the Joint Standoff Weapon (JSOW). These similar variants can be said to belong to the same munition 'family'. Each individual munition (variant) has a unique NNOR requirement, but all of the munitions in a single family share an industrial base. In particular, these weapons are often manufactured at common facilities, from similar parts, and by the same workforce. In some cases multiple variants are manufactured simultaneously, in other cases a production line alternates between several variants of a weapon. For munitions such as these that can be identified as belonging to a family, the industrial base constraints are consolidated in AIM.

While the munitions in a family are similar, the individual variants each have unique costs, and therefore do not necessarily represent equivalent per-unit revenues to the manufacturer. In order to account for this, the industrial base constraints of MSR and MPR are converted from units of quantity of munitions into units of total procurement cost. Then, the industrial base constraints for the individual munitions of a family can simply be summed to determine the constraints applied to the total family. In the AIM mathematical formulation, each munition is a member of a family, and each family consists of one or more munitions. Mathematically, each industrial base constraint can be applied to a family of munitions, although in practice most munitions are considered independently.

E. QUANTITY-BASED PRICING

Munition pricing data is given for quantities known as 'lots.' Each lot is represented by a lot count and a lot cost; the lot cost is the total cost to procure exactly that lot count of munitions. Each munition can have up to ten lots, each lot representing a larger block of munitions that might be procured in a single year. Procurements are not restricted to full-lot quantities. From the lot data, unit costs are derived and procurements costs for partial-lot quantities are linearly interpolated. In general, larger quantities of munitions can be procured at lower unit costs and so the munition unit cost curves are piecewise linear and generally concave.

In order to support these computations, each munition must be represented by at least two lots. The first is a "zero lot" and expresses the fixed cost penalty for a violation of the MSR. An example of a typical unit cost curve and the application of industrial base constraints is shown in Figure 5.

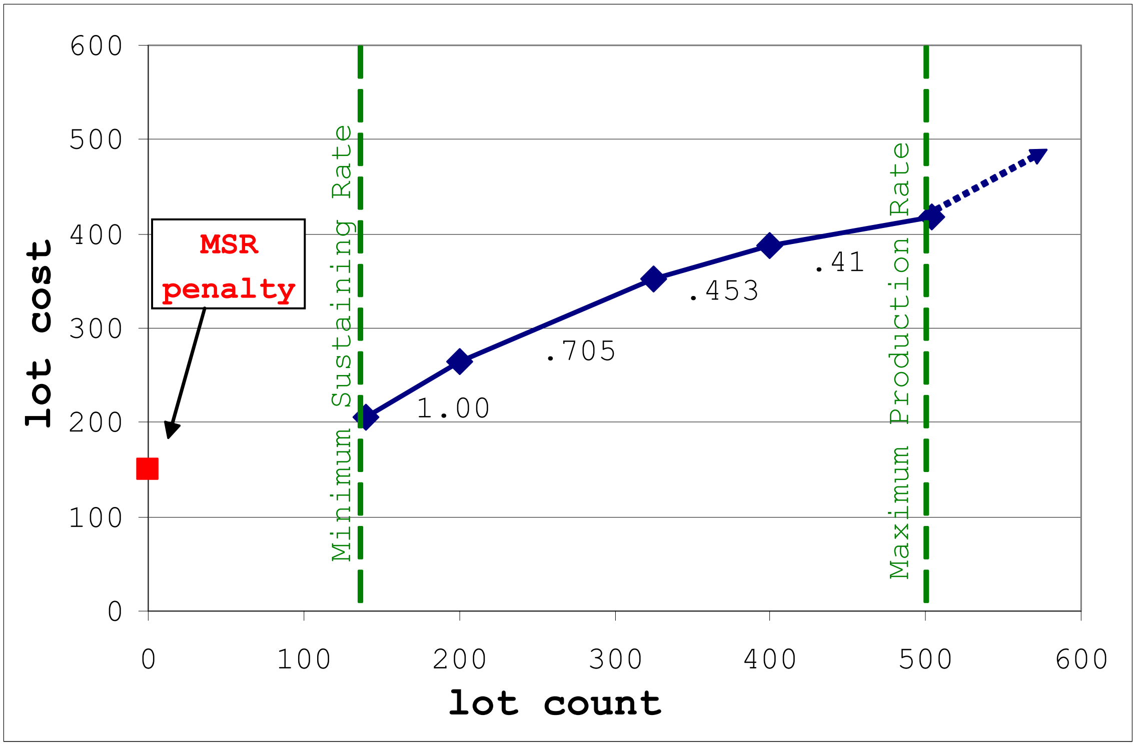


Figure 5. Sample Munition Unit Cost and Industrial Base Constraints
Unit costs generally decrease with increasing quantity. Violations of MPR result in additional per unit costs while violations of MSR result in a fixed cost penalty.

F. MAINTENANCE THROUGHPUT CONSTRAINTS

Munitions maintenance is performed at either a Navy owned and operated facility or at a civilian contractor site, and for some munitions can be done at either. In AIM, per-unit maintenance costs are considered fixed, regardless of quantity of maintenance performed.

Just as there are restrictions on minimum and maximum annual new munitions procurement, there are also constraints on the annual maintenance throughput. The maximum maintenance throughput is defined as the number of

munitions that can begin maintenance in a single year, across all available facilities, without significant improvements to those facilities. Violation of this maximum maintenance throughput constraint results in a relative increase in per-unit maintenance costs for all excess maintenance.

Similar to the Minimum Sustaining Rate for the procurement industrial base, there is a minimum annual maintenance throughput. However, since a portion of all maintenance is performed at Navy facilities (in fact, in most cases, Navy facilities are used to their capacity before civilian maintenance services are contracted), failure to meet this minimum throughput will not result in the loss of this capability. Instead, the minimum maintenance throughput represents the minimum count of munitions for which the facility operates efficiently; below this count the facility is not cost effective and the value of the maintenance performed does not justify the cost of the facility.

In AIM, annual maintenance is allowed for any non-negative count of munitions up to the total available in the maintenance inventory from previous years plus those due for maintenance in the current year. Violation of the minimum annual throughput results in a penalty equal to the difference between the cost of the minimum maintenance throughput and the cost of actual maintenance performed, multiplied by a scaling factor that slightly increases the penalty as the magnitude of the violation increases. In this way, the cost of maintenance performed plus penalty will always meet or exceed the minimum maintenance

throughput cost. The scaling factor is employed to provide additional motivation to conduct maintenance when possible.

A maintenance constraint applies to each munition 'family', as with the procurement industrial base constraints. Both threshold values and actual maintenance conducted, in quantities of munitions, are converted to costs.

G. BUDGET CONSTRAINTS

Budget inputs to AIM include an upper and lower bound for annual procurement spending and an upper bound for maintenance spending. Constraints on spending, in both categories, are applied cumulatively, providing some flexibility to 'save' some funding from an earlier year and apply it to a later year's activities. The upper bounds on both procurement and maintenance spending are hard constraints. The lower bound on procurement spending represents the requirement, in governmental budgeting, to spend what is appropriated or risk losing it. As such, a violation of the lower bound on annual procurement spending results in a penalty applied in the objective function equivalent to a reduction in the count of the overall inventory equal to the maximum number of munitions that could have been purchased for the amount of money that was underspent.

Total annual procurement and maintenance spending, which include any penalties assessed for violations of industrial and maintenance base, are charged against the appropriate budget in the year in which the action is begun, notwithstanding any delay for the new or maintained

munition to arrive in the active inventory. Future-year spending (beyond year one) is discounted according to the Office of Management and Budget’s real discount rate for cost effectiveness, lease purchase, and related analysis [OMB, 2003].

H. LIMITING CHANGES TO LEGACY PLANS

AIM is more useful when it can be trusted to revise a legacy solution that may already have been closely scrutinized without unnecessarily revising too many details. Turbulence in revised solutions is aggravating and can lose trust by planners investing a lot of time working through complex procurement scenarios. Optimization has a well-earned reputation for amplifying small changes in inputs to breathtaking revisions. This is unacceptable.

In order to provide the ability to update solutions for future years and to conduct some basic sensitivity analysis, the AIM formulation is augmented with some additional constraints to allow for modeling with persistence [Brown, Dell, and Wood, 1997]. Of particular interest is the ability to limit the changes in the number of a particular munition to be procured in a given year, and the ability to prevent significant changes to the capacity of the industrial base as defined in a legacy plan.

To accomplish the former, the quantity of munitions procured in a revised plan is restricted by a set of ranged persistent constraints [Brown, Dell, and Wood, 1997, p.19] that inflict penalties for violations of an allowable

relative deviation (above or below) from the quantity of munitions procured during that same period in a legacy plan. The range of the allowable deviation can vary throughout the eight annual time periods, but is similar for each munition.

To stabilize the capacity of the industrial base, the model enforces penalties on any revision in the status of a production facility. In particular, penalties are incurred for every facility for which the revised solution results in zero production when the legacy solution indicated that the facility would be in use. Likewise, a penalty is incurred for each facility that is not employed in the revised solution and which was active in the legacy plan. These constraints can be applied to any continuous range of years but must begin in year one.

I. OBJECTIVE FUNCTION

The main goal of AIM is to raise the overall capability of the munitions inventory. AIM achieves this by calculating, for each year, the minimum tier achieved over all munitions. The objective function is the sum over the planning horizon of this minimum tier, and AIM maximizes this sum. This technique for quantifying the overall capability of the inventory ensures that there is no capability gap created for one munition as a result of overly aggressive increases in capability of the remaining munitions. The result is that, while munitions may start with radically different initial relative inventories, the AIM recommendation will guarantee some minimum capability for every munition in each year.

Because the individual tier levels are integer, the sum of the minimum tier levels is as well, and this might admit a large number of equivalent plans. In order to differentiate between a potentially large number of indistinguishable plans, an additional term is included to express the relative count of the overall total inventory. Summing the total inventory count over all munitions and all years, and dividing by the sum of all munitions' Total Munition Requirements, over all years, accomplishes this.

There are also a number of penalties that are assessed in the objective function, including those for underspending the procurement budget, for failing to conduct timely maintenance, and several that assess violations of persistence constraints. The first two are incorporated in the measure of total annual inventory. The overall inventory, in each year, is reduced by the penalty for underspending, as described above, and by a fraction (fixed for all years) of the total number of munitions in the maintenance inventory.

The persistence penalty for changing the status of a production facility is applied as a unit decrease for each such occurrence. The effect is that every production facility that is unable to maintain a consistent status from the legacy plan to the revised plan will reduce the minimum tier achieved in that year by one. A failure to meet the allowable range for individual munition procurement results in a penalty equal to the difference between the allowable change and the actual change, in percentages. Therefore, the effect of each additional 1% change in annual procurement for each munition between the

legacy and the revised plan is to reduce the value of the overall relative inventory by 1%.

This basic objective function can be modified to emphasize capability in some years more than others. We use this to speed up the search for an initial solution. While the formulation of the model generally encourages the early improvement of munitions with low tier levels, computational experience has shown that heavily weighting the early years results in significantly improved procurement plans and faster turnaround.

IV. EXPOSITORY MODEL FORMULATION

The expository formulation presented in this chapter is a greatly simplified version of the AIM model. The full AIM formulation is provided in Appendix B.

In this simplified version of the model, the objective function includes only the sum of minimum tier levels. Additionally, munition maintenance requirements are not shown, the maximum production rate is considered a hard limit on annual procurement, the concept of munition 'families' is not displayed, munitions arrive in the inventory in the same year in which they are procured, procurement spending is not discounted in future years, elastic constraints are omitted, and the options for revising a legacy plan are not included.

A. INDICES AND SETS

$m \in M$ Munition, any munition for which NNOR requirements are generated, currently NNOR considers 190 munitions, we have data for 19 of them

$y \in Y$ Year of the planning horizon, Y={1,...,8}

$t \in T$ Tier level, T={1,...,num_tiers}

$l \in L$ Procurement pricing lot, L={1,...,10}

B. DATA

$lot\_count_{m,l}$ Number of munition m in lot l

$lot\_cost_{m,l}$ Procurement cost for the full quantity of lot l of munition m

$unit\_cost_{m,l}$	Unit cost per munition *m* in lot *l*.
$min\_sust\_rate_m$	Minimum production Sustaining Rate (MSR) for munition *m*
$max\_prod\_rate_m$	Maximum Production Rate (MPR) for munition *m*
$init\_invent_m$	Initial on-hand inventory of munition *m* at the beginning of the planning horizon
$expend_{m,y}$	Expected annual expenditures, in training and in operations, for munition *m* in year *y*
$proc\_budget\_low_y$, $proc\_budget\_upp_y$	Lower and upper bounds for annual procurement budget band in year *y*
$mpr\_pen\_rate_m$	Proportional additional penalty cost to munition *m* for exceeding its MPR
$tier\_lvl_{m,t,y}$	Number of weapons of type *m* in year *y* required to reach tier *t*

C. VARIABLES

$PROCURED_{m,y}$	Number of munition *m* procured during year *y*
$LOT\_PROCURED_{m,l,y}$	Number of munition *m* procured from lot *l* in year *y*
$PROC\_COST_{m,y}$	Total cost of procurement of munition *m* in year *y*

$DELIVERED_{m,y}$	Number of munition m delivered during year y from both new procurement and maintenance
$ACTIVE\_INV_{m,y}$	Number of munition m in the usable inventory at the end of year y
MIN_TIER_{y}	Minimum tier achieved of all munitions in year y
$CUM\_TIER\_REACHED_{m,t,y}$	Binary variable, 1 if munition m is in tier t or below in year y
$LOT\_INDICATOR_{m,l,y}$	Binary variable, 1 if munition m is being procured in lot l during year y
$MEET\_MSR_{m,y}$	Binary variable, 1 if munition m satisfies its MSR in year y

D. CONSTRAINTS AND OBJECTIVE FUNCTION

$$\text{MAXIMIZE} \quad \sum_{y} \text{MIN\_TIER}_{y}$$

Subject to:

$$\text{ACTIVE\_INV}_{m,y} = \left[\text{init\_invent}_{m}\right]_{y=1} + \left[\text{ACTIVE\_INV}_{m,y-1}\right]_{y>1} + \text{PROCURED}_{m,y} - \text{expend}_{m,y} \qquad \forall m,y \qquad (1)$$

$$\text{PROCURED}_{m,y} = \sum_{l} \text{LOT\_PROCURED}_{m,l,y} \qquad \forall m,y \qquad (2)$$

$$\left[\left(\text{lot\_count}_{m,l+1}-\text{lot\_count}_{m,l}\right) * \text{LOT\_INDICATOR}_{m,l+1,y}\right]_{l<10}$$
$$\leq \text{LOT\_PROCURED}_{m,l,y} \leq$$
$$\left(\left[\text{lot\_count}_{m,l+1}\right]_{l<10}+\left[\text{tier\_lvl}_{m,'16',y}\right]_{l=10} - \text{lot\_count}_{m,l}\right) * \text{LOT\_INDICATOR}_{m,l,y}$$
$$\forall m,y,l \qquad (3)$$

$$\text{MEET\_MSR}_{m,y} * \text{min\_sust\_rate}_{m} \leq \text{PROCURED}_{m,y}$$
$$\leq \min\left\{\text{max\_prod\_rate}_{m}, \text{MEET\_MSR}_{m,y} * \text{tier\_lvl}_{m,'16',y}\right\} \qquad \forall m,y \qquad (4)$$

$$\text{PROC\_COST}_{m,y} = \sum_{l}\left(\text{LOT\_PROCURED}_{m,l,y} * \text{unit\_cost}_{m,l}\right) \qquad \forall m,y \qquad (5)$$

$$\sum_{y'=1}^{y} \text{proc\_budget\_low}_{y'} \leq$$
$$\sum_{m}\sum_{y'=1}^{y}\left(\text{PROC\_COST}_{m,y'} + \left(1-\text{MEET\_MSR}_{m,y'}\right) * \text{msr\_pen}_{m}\right)$$
$$\leq \sum_{y'=1}^{y} \text{proc\_budget\_upp}_{y'}$$
$$\forall y \qquad (6)$$

$$\text{tier\_lvl}_{m,'1',y} * \text{CUM\_TIER\_REACHED}_{m,'1',y} +$$
$$\sum_{t=2}^{16}\left[\text{tier\_lvl}_{m,t,y} * \left(\text{CUM\_TIER\_REACHED}_{m,t,y} - \text{CUM\_TIER\_REACHED}_{m,t-1,y}\right)\right] \leq$$
$$\text{ACTIVE\_INV}_{m,y} \leq$$
$$\text{tier\_lvl}_{m,'16',y} * \left(\text{CUM\_TIER\_REACHED}_{m,'16',y} - \text{CUM\_TIER\_REACHED}_{m,'15',y}\right) +$$
$$\sum_{t=1}^{15}\left[\left(\text{tier\_lvl}_{m,t+1,y}-1\right) * \left(\text{CUM\_TIER\_REACHED}_{m,t,y} - \text{CUM\_TIER\_REACHED}_{m,t-1,y}\right)\right]$$
$$\forall m,y \qquad (7)$$

$$\mathrm{CUM\_TIER\_REACHED}_{m,t+1,y} \geq \mathrm{CUM\_TIER\_REACHED}_{m,t,y} \qquad \forall m,y,\ t<16 \qquad (8)$$

$$\mathrm{MIN\_TIER}_{y} \leq \sum_{t=2}^{16} \begin{pmatrix} t*\mathrm{CUM\_TIER\_REACHED}_{m,t,y} \\ -\mathrm{CUM\_TIER\_REACHED}_{m,t-1,y} \end{pmatrix} + \mathrm{CUM\_TIER\_REACHED}_{m,'1',y} \qquad \forall m,y \qquad (9)$$

E. BRIEF VERBAL DESCRIPTION

The objective function expresses the sum of the annual minimum tier achieved.

Constraints:

(1) These are inventory balance equations for each active (combat useable) munition.

(2) This equation determines the total number of a munition procured in a given year by summing procurements over all individual lots.

(3) These constraints require that an individual lot procurement is no larger in count than the count of the entire lot (or the NNOR total requirement when purchasing from the last lot) and that a munition may not be procured from the next lot without procuring the entire previous lot.

(4) These equations enforce the maximum production rate (MPR) for each munition (in this basic formulation, production in excess of the MPR is prohibited) and determine whether the minimum sustaining production rate (MSR) for a munition has been met. A failure to meet the MSR results in a penalty on overall procurement spending.

(5) Each equation determines the total cost of new procurement of a single munition in a given year.

(6) These constraints enforce the upper and lower bounds on cumulative procurement budget spending. Annual procurement spending includes the cost of new munitions plus any penalty assessed for violation of the MSR.

(7) These constraints determine which tier has been reached based on a current (active) inventory count.

(8) These constraints require the tier reached indicator variable to be non-decreasing.

(9) Each constraint determines the minimum tier achieved in a given year.

V. IMPLEMENTATION AND RESULTS

A. DATA COLLECTION AND SCENARIO

Data for nineteen U.S. Navy strike munitions has been provided by Naval Ammunitions Logistics Center (NALC), a sample of this data is included in Appendix A. Due to the security classification of NNOR requirements, all references to actual current inventories and requirements will be listed as proportions of the NNOR Total Munition Requirement.

Values for fixed and annual global parameters, as shown in Table 4 and Table 5, have also been provided by NALC except in the case of the discount rate, which was taken from the OMB web site [OMB, 2003]. The procurement budget values are approximated based on the 2004 President's Budget for U.S. Navy Weapons Procurement. The maintenance budget is intended to allow for significant flexibility to maintain a majority of the inventory in combat useable condition. While training expenditures for future years are estimated, operational expenditures are not. The AIM recommendation uses the sixteen-tier tier structure described in Chapter II.

Procurement Budget – Upper Limit	1,100 M$/year
Procurement Budget – Lower Limit	990 M$/year
Discount Rate	0.023

Table 4. Fixed Global Parameters for AIM and BASELINE Model Plans

Procurement budget values are a portion of the Navy Weapon Procurement budget from the FY04 President's Budget. NALC determined the appropriate value for the nineteen munitions considered. Discount rate is determined from the OMB Real Discount Rate.

	Years							
	1	2	3	4	5	6	7	8
Maintenance Budget (in M$)	30	40	50	60	70	80	90	100

Table 5. Annual Global Parameters for AIM and BASELINE Model Plans

Maintenance budget allowances increase to accommodate a growing total inventory.

B. BASELINE RECOMMENDATION

In order to provide a benchmark against which to compare AIM procurement recommendations, we wrote an integer linear program to mimic the current process for generating procurement recommendations. The Naval Ammunition Logistics Center (NALC) provided the insight necessary to mathematically describe this subjective process. This plan, referred to as the *baseline* plan, applies the set of priorities currently in use by decision makers at the Navy's Fleet Readiness and Logistics organization and optimizes the metric currently used to measure munition capability.

The baseline plan manages an active and maintenance inventory and handles maintenance requirements, industrial base constraints, spending and budgets. It employs the same variable unit cost equations as are used by AIM. To measure munition capability, for each munition, this model tracks current active inventory as a proportion of its NNOR TMR. Annual procurement priorities are: first, to replace expended munitions, then to satisfy industrial base constraints, and finally to improve munition capability. In particular, the objective function is given by the sum of the minimum relative inventory over all years and all munitions. Additionally, it also includes objective function penalties for underspending the procurement budget and failing to conduct timely maintenance.

The baseline model automates all of the decisions that are currently made subjectively to determine a procurement plan. This plan is the optimal (as defined by current priorities and metrics) feasible procurement plan for any given scenario. This model in itself may prove useful to current munitions procurement planners.

C. AIM COMPUTATIONAL EXPERIENCE

Recommendations from AIM have been generated on a Dell Precision 340 desktop computer with a Pentium IV 2.0 GHz processor and 1 GB of RAM. AIM is written in the GAMS language and is solved with the CPLEX solver, version 7.5.0 [ILOG CPLEX, 2003].

1. Exploration of Heuristics

Initially, AIM required many hours to generate a procurement plan. The time it took to find a "reasonably good" feasible solution was particularly long. In an effort to shorten the total turnaround time we investigated the use of a heuristic to identify a good initial candidate solution. This initial candidate solution could then be passed to AIM and improved - arriving at the final procurement plan much more quickly than AIM was doing alone. Ideally, the heuristic would generate a procurement plan that was nearly as good as the AIM procurement plan and therefore it might also be used independently of AIM.

The heuristic we used was myopic (it looks at only one year at a time) and "greedy" (it improves tier levels of the minimum tier level munitions every time it can).

a. Brief Verbal Description

The heuristic follows these basic steps:

1. For all munitions, in all years, the number of munitions procured is set to the Minimum Sustaining Rate (MSR)

2. For years 1 through 8,

    a. Until the annual maintenance budget is expended, conduct maintenance for each munition (in increasing tier level order). The number of items maintained, of each munition, is the minimum of: the number of items that require maintenance, the number of items required to reach the next tier level, and the number of items possible with the remaining maintenance budget.

b. Until the annual procurement budget is expended, procure additional units for all munitions in the minimum tier (in decreasing order of the cost of procurement to reach the next tier level). The number of additional units procured, of each munition, is the minimum of: the number of units required to reach the next tier level, and the number of items possible with the remaining procurement budget.

b. Heuristic Results

This heuristic will generate a complete procurement plan in only a few minutes. However, comparison of the sums of annual minimum tier levels shows that the heuristic procurement plan is not nearly as good as the AIM procurement plan.

While modifying the heuristic and analyzing resultant performance, we identified that the heuristic performed best when it placed the highest emphasis on the early years of the planning horizon. This realization lead to the use of weights in the AIM objective function as introduced in Chapter 3. While ultimately the heuristic failed to contribute directly by providing AIM an initial candidate solution, indirectly it resulted in a significant improvement in AIM turnaround time.

2. AIM Recommendation

The use of weights in the objective function increases the emphasis on early years and significantly improves

solution times. We use an exponential weighting of the objective function to find an initial candidate solution:

$$\text{weight}(y) = 2^{(9-y)} \quad \text{where } y \in \text{Years}.$$

This initial candidate solution is then provided as an incumbent solution to the model to solve again, this time with all weights equal. A typical model for this data includes 6,900 equations and 6,500 variables (half of which are binary) and solving in this manner generates solutions in approximately an hour and a half.

As an example of how the use of capability tier levels is reflected in annual procurements, consider the results for one particular munition over the eight years of the solution, in this case, the Hellfire missile. Figure 6 shows the increasing inventory, both in relative count (proportion of the TMR) and in capability (measured by tier level).

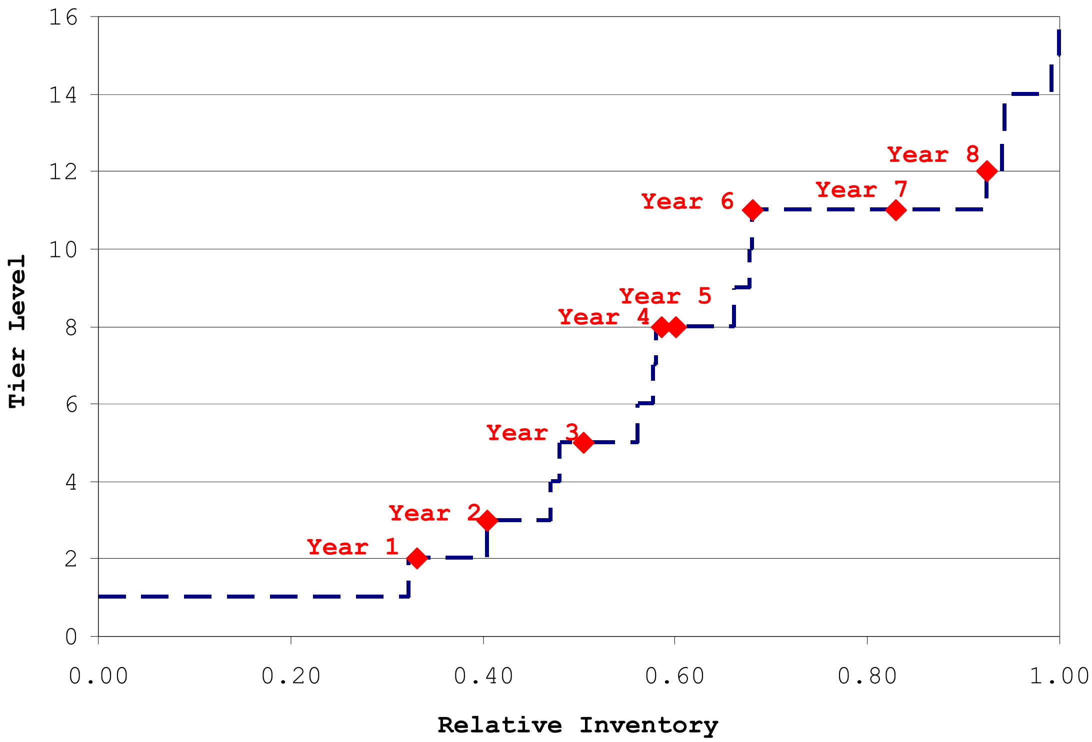


Figure 6. Increasing Capability and Relative Inventory of Hellfire Missiles
Projected annual inventory counts for the Hellfire missile are shown in terms of both relative inventory (inventory count in relation to TMR) and tier level. For example, very few munitions are procured in year five, resulting in no increase in tier level from year four. Steep portions of the curve identify significant increases in capability for relatively small increases in size of inventory.

D. COMPARISON OF RESULTS

Consider the metric currently in use by munitions procurement planners: the size of the inventory as a percentage of the Total Munition Requirement (TMR). Table 6 compares the initial inventory count to the inventories at the end of Year 8 for both the baseline plan and AIM. These same end-of-year 8 inventories are depicted

graphically in Figure 7. In thirteen of the nineteen munitions considered AIM achieves a larger final munition inventory than the baseline model. Additionally, when considering the sum of all individual munition inventories as a whole, the consolidated AIM inventory is more than 23,600 munitions larger than the baseline inventory, roughly an 8.2% improvement.

Munition	Initial Inventory	BASELINE Plan	AIM Plan
AMRAAM	42.25%	81.36%	70.50%
GBU-24 Kit	49.54%	81.36%	74.21%
GBU-16 Kit	73.03%	87.75%	99.99%
GBU-12 Kit	34.88%	81.36%	100.00%
GBU-10 Kit	63.56%	81.36%	95.76%
Maverick	100.00%	100.00%	67.53%
Hellfire	33.19%	81.36%	92.46%
HARM	94.96%	91.39%	67.95%
Sidewinder	79.87%	91.69%	98.98%
JDAM	32.79%	81.36%	77.39%
JSOW (Unitary)	3.40%	81.36%	90.39%
JSOW (Baseline)	22.60%	83.17%	84.35%
MK84	72.29%	98.62%	100.00%
MK83	78.59%	81.36%	100.00%
MK82	48.25%	92.98%	96.84%
Tomahawk 109E	5.91%	81.65%	85.98%
Tomahawk UGM109D	37.74%	82.77%	70.57%
Tomahawk RGM109D	42.02%	82.30%	85.55%
SLAM-ER	86.54%	100.00%	100.00%

Table 6. Inventory Comparison of Initial Inventory to BASELINE Plan and AIM Plan (End-of-Year 8 Relative Inventories)

Inventory values are given for the quantity of munitions in the active inventory, relative to the Total Munition Requirement (TMR) - at the beginning of Year 1 (Initial Inventory) and at the end of Year 8 (BASELINE and AIM plans).

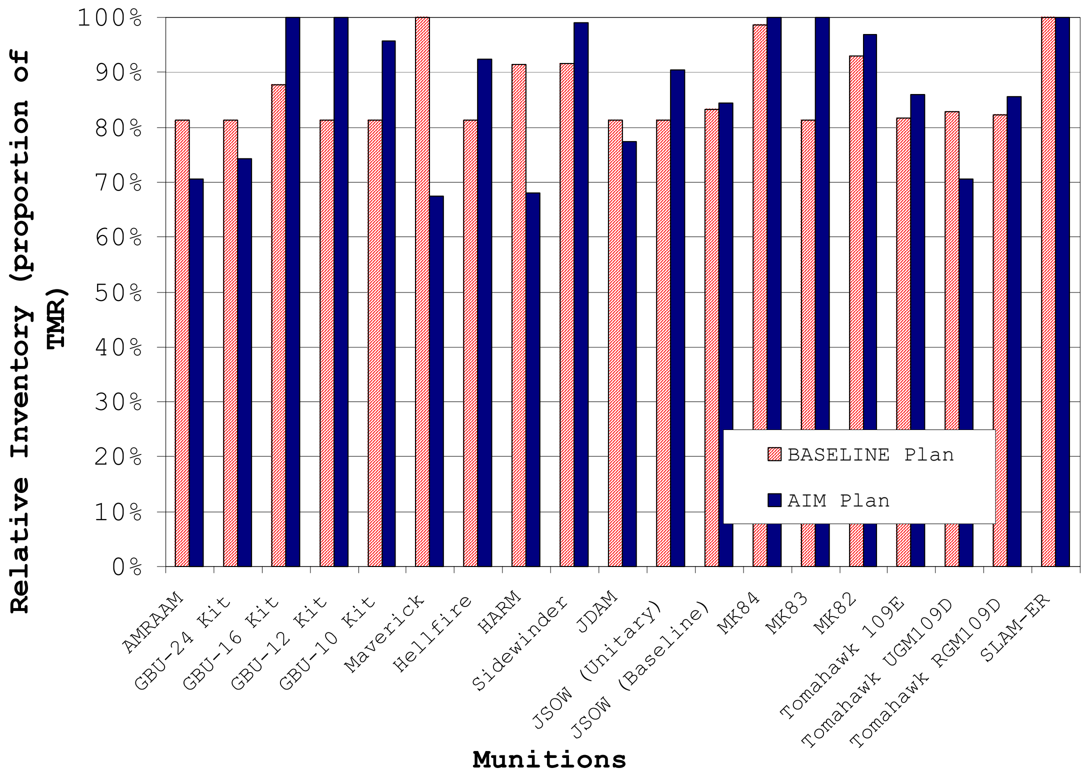


Figure 7. Comparison of BASELINE Plan and AIM Plan (End-of-Year 8 Relative Inventories) Individual munition relative inventory levels are shown as a percentage of TMR, determined from the active inventory counts at the end of year 8, for the AIM plan and the BASELINE plan. AIM achieves larger individual munition inventories for thirteen of nineteen munitions.

Alternately, the two solutions can be compared by the tier level metric for measuring capability of a munitions inventory. With this metric AIM does even better. The same baseline plan is considered; with the AIM tier level structure applied to the resulting Year 8 inventories. These are compared to the AIM plan in Table 7 and are shown graphically in Figure 8. Compared this way, AIM achieves a

tier level as good as or better than the BASELINE plan in the case of fifteen of the nineteen individual munitions.

Munition	Initial Inventory	BASELINE Plan	AIM Plan
AMRAAM	3	12	11
GBU-24 Kit	5	11	11
GBU-16 Kit	13	15	15
GBU-12 Kit	4	15	16
GBU-10 Kit	11	14	14
Maverick	16	16	11
Hellfire	2	11	12
HARM	14	14	11
Sidewinder	12	14	15
JDAM	1	11	11
JSOW (Unitary)	1	11	12
JSOW (Baseline)	2	12	12
MK84	11	14	16
MK83	14	14	16
MK82	6	14	14
Tomahawk 109E	1	12	14
Tomahawk UGM109D	3	14	12
Tomahawk RGM109D	3	11	12
SLAM-ER	11	16	16

Table 7. Tier Level Comparison of Initial Inventory to BASELINE Plan and AIM Plan (End-of-Year 8 Tier Levels)
Tier level values are determined from active inventory counts at the beginning of Year 1 (Initial Inventory) and at the end of Year 8 (BASELINE and AIM plans). AIM achieves tier levels as good as or better than the BASELINE plan for fifteen of the nineteen munitions.

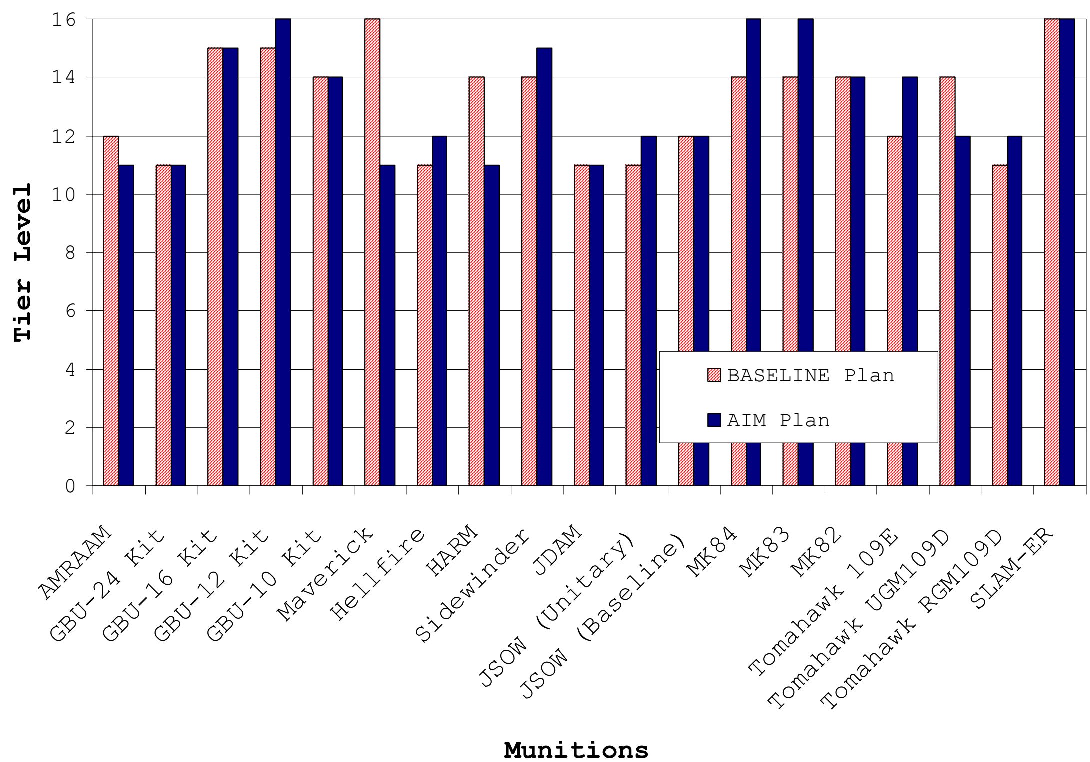


Figure 8. Comparison of BASELINE Plan and AIM Plan (End-of-Year 8 Tier Levels)
Individual munition tier levels measured from active inventory counts at the end of year 8 are shown, for the AIM plan and the baseline plan. AIM achieves tier levels as good as or better than the BASELINE plan for fifteen of the nineteen munitions.

While comparison of inventory size and capability at the end of year 8 both indicate that AIM is superior, the end-of-time-horizon states may not be the most appropriate comparison. The agencies involved in munitions planning attempt to generate estimates for expenditures, requirements, and procurements for an eight- to ten-year period, but they recognize that the accuracy of those estimates erodes rapidly as they look further into the future. In fact, the most critical period for these

estimates is from two to four years into the future due to the length of time required for the military planning, programming, and budgeting POM horizon. Therefore, the effect that a procurement plan has on the capability of the inventory in these near years is probably a more significant judge of its value.

Figures 9, 10, and 11 compare the individual munition capability tier levels from AIM and the BASELINE plan calculated from inventory counts at the end of years 2, 3, and 4, respectively. In these years, AIM achieves individual tier levels as good as or better than the BASELINE plan for fourteen, fifteen, and thirteen (respectively) out of the nineteen munitions.

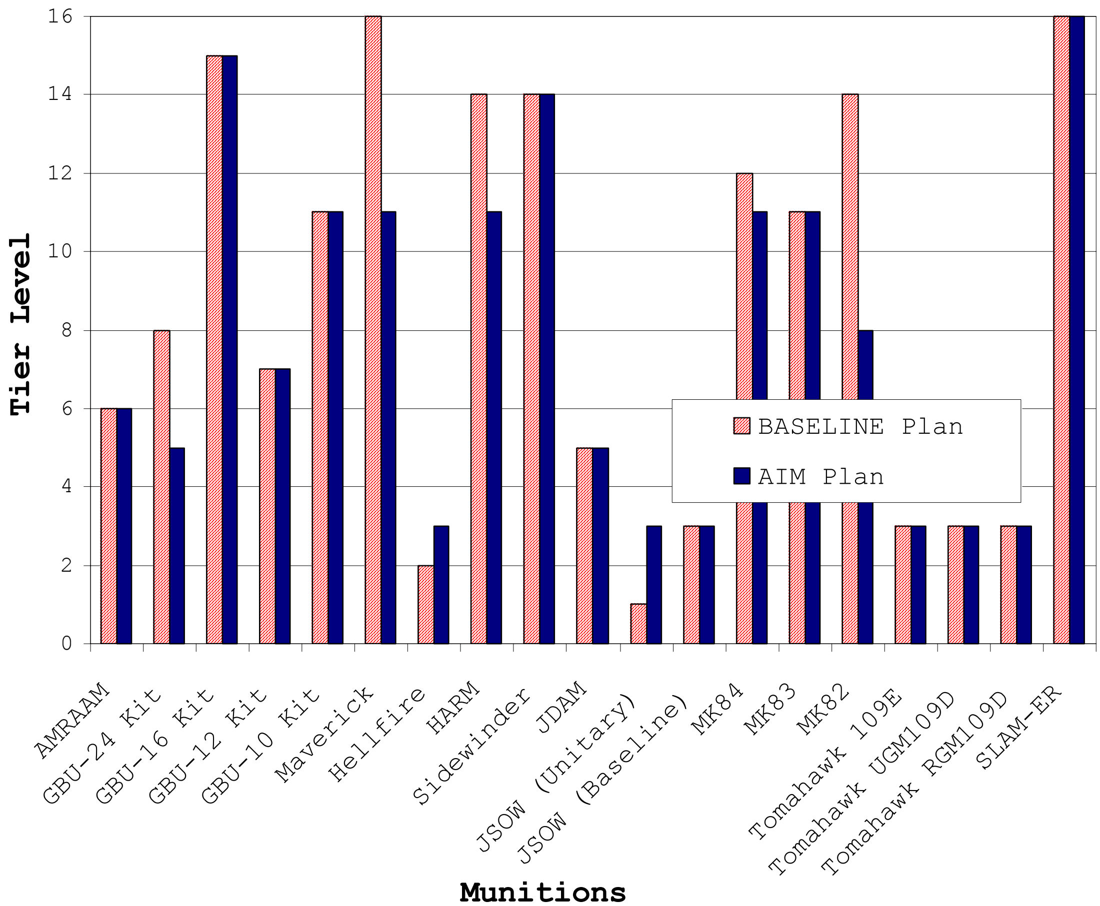


Figure 9. Comparison of BASELINE Plan and AIM Plan (End-of-Year 2 Tier Levels)

Individual munition tier levels measured from the active inventory counts at the end of year 2 are shown, for the AIM plan and the BASELINE plan. AIM achieves tier levels as good as or better than the BASELINE plan for fourteen of the nineteen munitions.

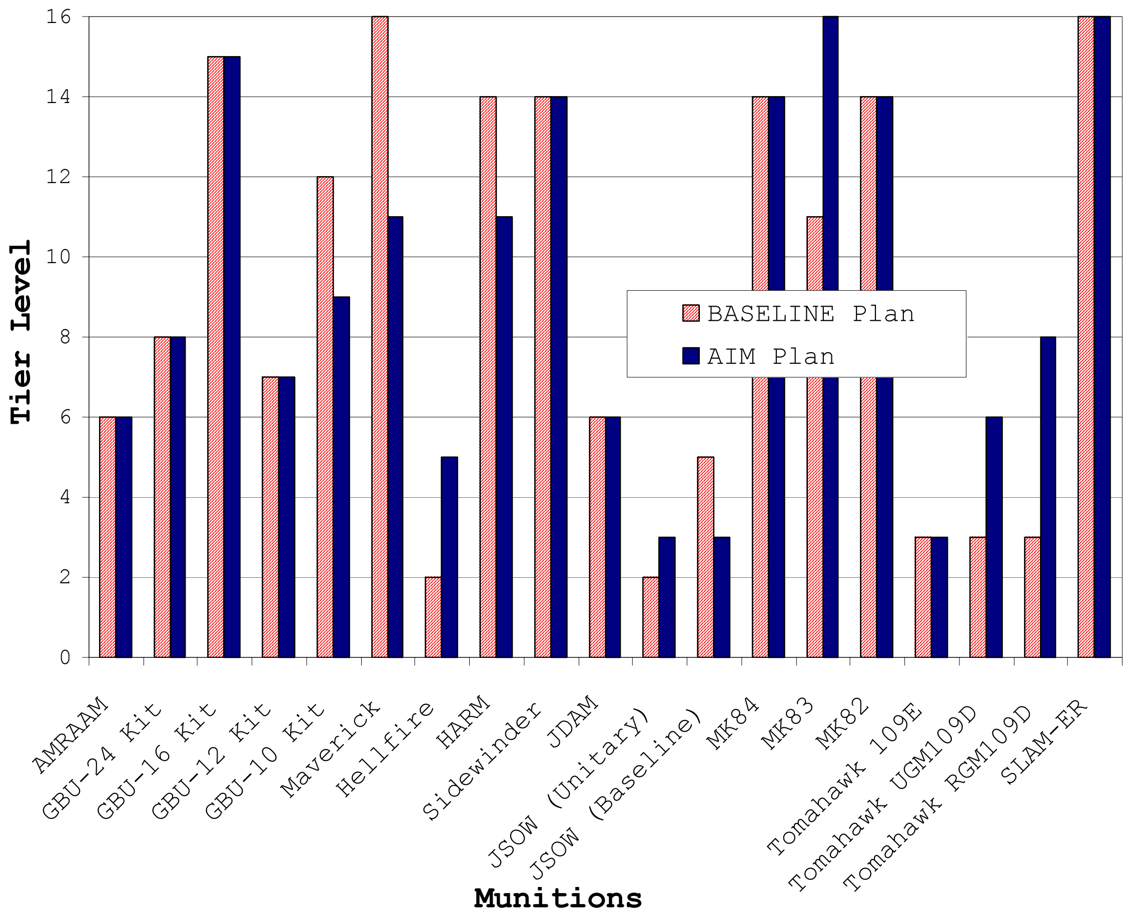


Figure 10. Comparison of BASELINE Plan and AIM Plan (End-of-Year 3 Tier Levels)

Individual munition tier levels measured from the active inventory counts at the end of year 3 are shown, for the AIM plan and the BASELINE plan. AIM achieves tier levels as good as or better than the BASELINE plan for fifteen of the nineteen munitions.

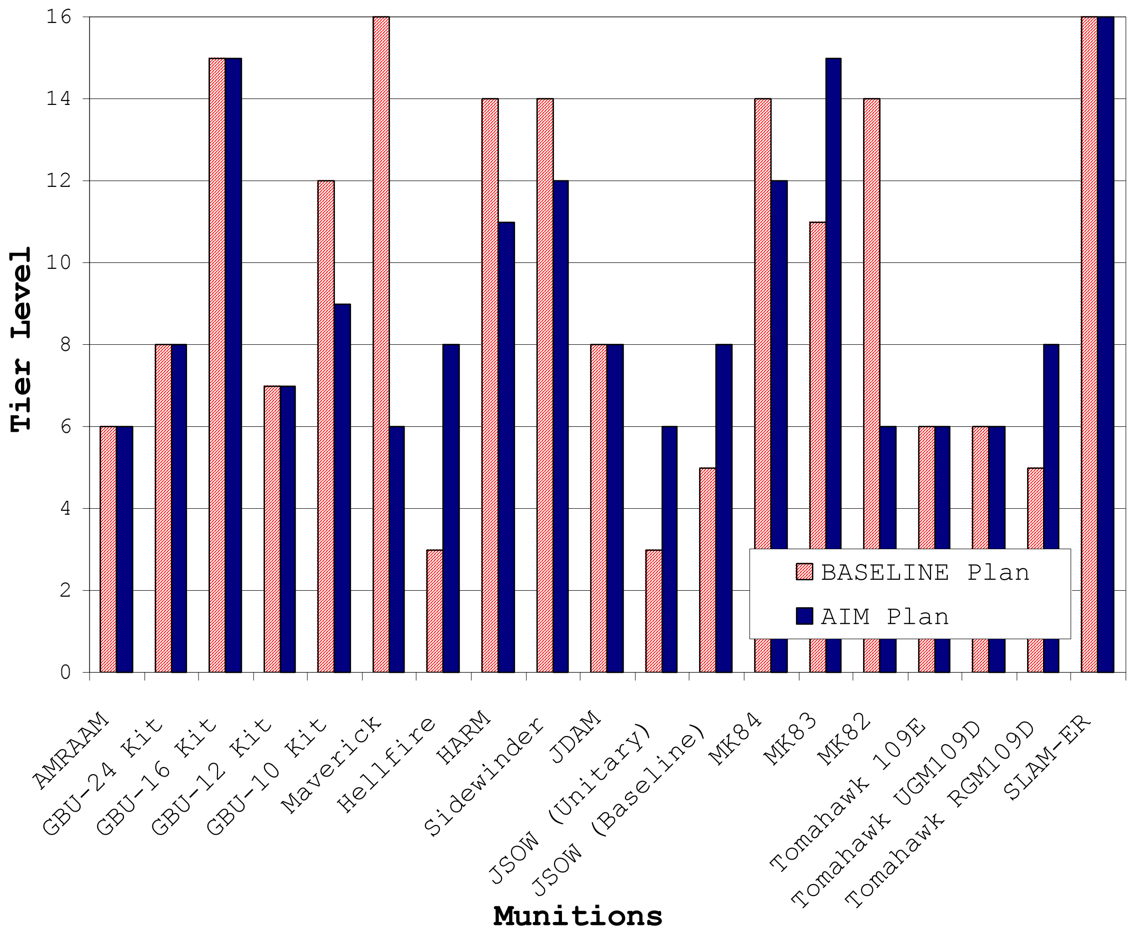


Figure 11. Comparison of BASELINE Plan and AIM Plan (End-of-Year 4 Tier Levels)
Individual munition tier levels measured from the active inventory counts at the end of year 4 are shown, for the AIM plan and the BASELINE plan. AIM achieves tier levels as good as or better than the BASELINE plan for thirteen of the nineteen munitions.

The smoothing effect of AIM is even more significant. AIM is more effective at improving the inventory count of munitions with low tier levels while simply sustaining those with high tier levels. Table 8 shows a comparison of the population standard deviation of individual munition tier levels for years 2 through 4. AIM achieves lower

variance in individual munition capability in each of these three years, and also reduces the variability by more than 25% in this time period, while the BASELINE plan produces only a 14% improvement.

	Year 2	Year 3	Year 4
BASELINE plan	5.18	5.09	4.45
AIM plan	4.39	4.43	3.29

Table 8. Comparison of the Variability of Munition Tier Levels Between BASELINE Plan and AIM Plan
Population standard deviation of the nineteen individual munition tier levels for Years 2, 3, and 4 from the BASELINE plan and the AIM plan are shown. AIM achieves lower tier level variability in each year and a significantly better reduction in variability over this same period.

Conducting a side-by-side comparison of the BASELINE plan with the AIM plan for all eight years indicates that AIM is superior throughout the entire planning horizon. Figure 12 shows the number of individual munitions (out of nineteen) for which the capability achieved by AIM is as good as or better than the capability provided by the BASELINE plan, by year.

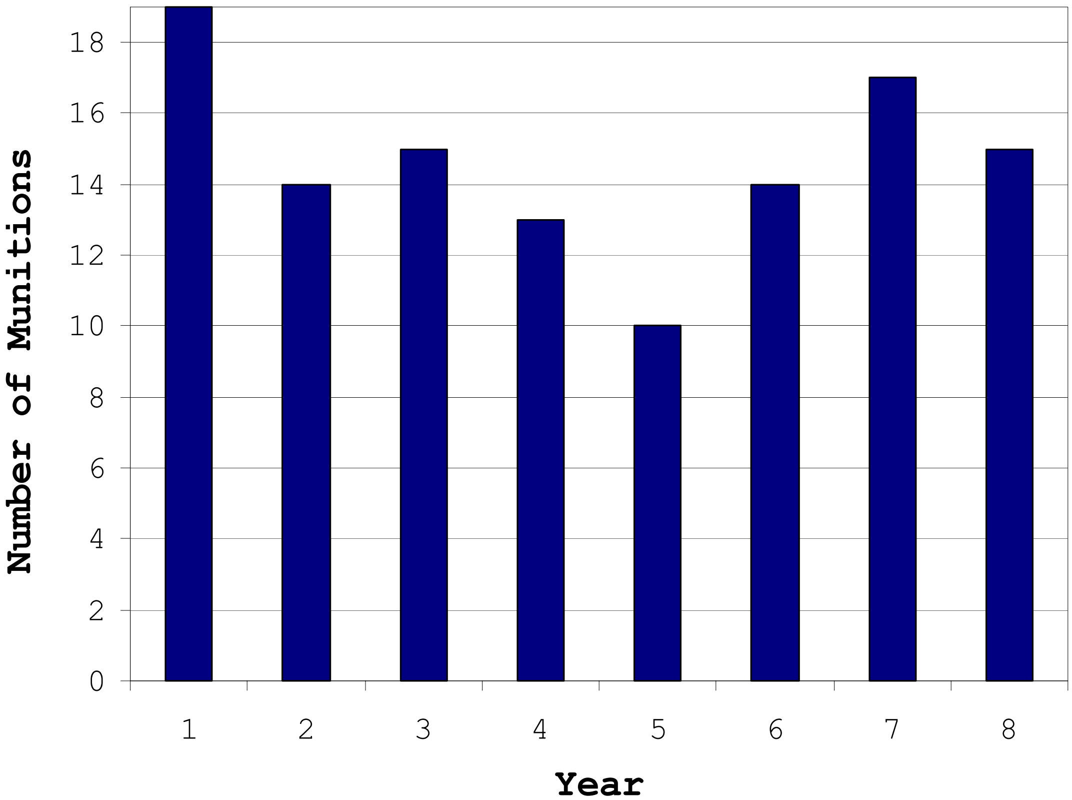


Figure 12. Summary of AIM-Improved Capability Munitions (By Year)
AIM consistently achieves a tier level as good as or better than the BASELINE plan for a majority of the munitions --- in most years, approximately 2/3 of all munitions --- throughout the entire planning horizon.

Similarly, the minimum tier achieved by all munitions in a given year is a key indicator of the overall capability of the entire inventory. Once again, AIM is superior to the BASELINE plan. In particular, as shown in Figure 13, the minimum tier level achieved by AIM rapidly increases while the baseline plan lags in the critical years.

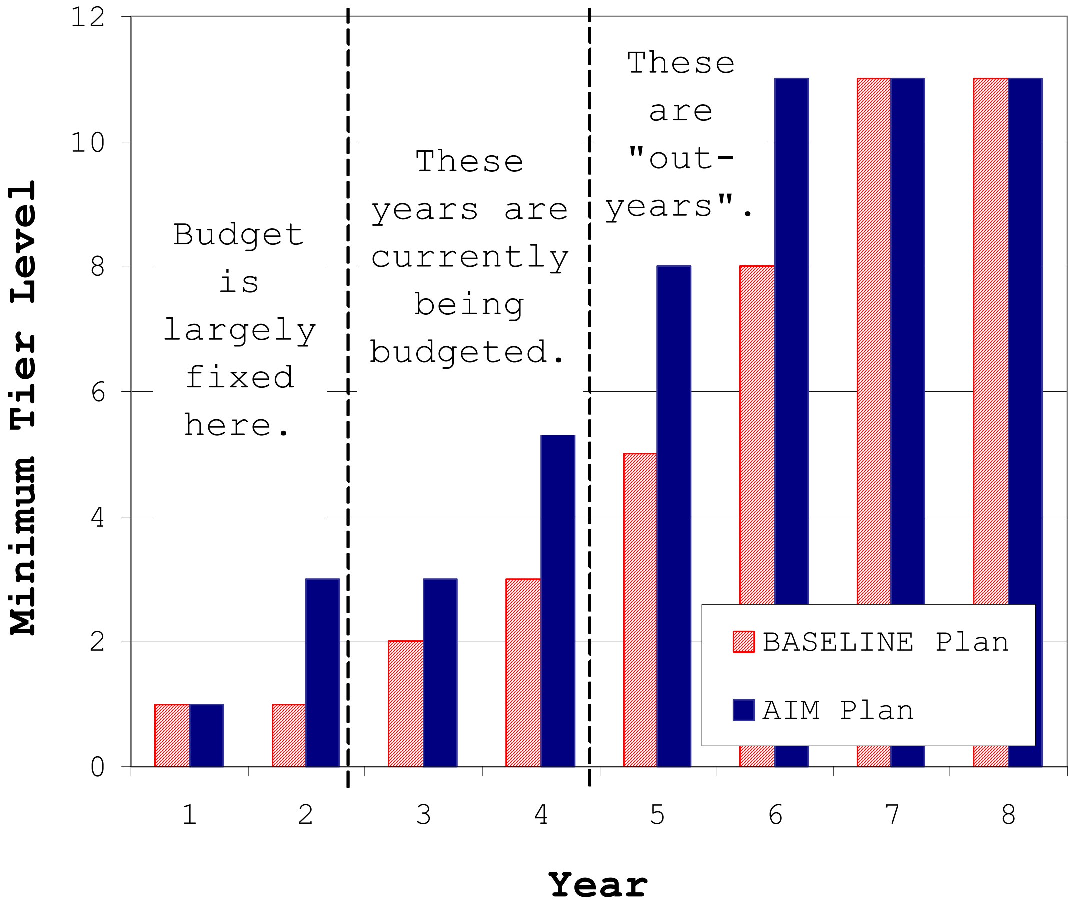


Figure 13. Comparison of Minimum Tier Levels (By Year)

The minimum tier level achieved by all individual munitions in each year of the plan is shown, for the AIM plan and the BASELINE plan. The AIM minimum tier level jumps quickly in year 2 and again in years 4 through 6 while the BASELINE plan minimum tier lags behind. Due to the length of the planning, programming, and budgeting process, the budgets for the first two years are fairly fixed. The next two years are critical, these are the budgets that are currently being planned. Beyond year four are important planning years, current procurement plans will be revised in the future to determine these years' budgets.

VI. CONCLUSION

A. SUMMARY

Planning munitions procurement for the U.S. Navy is a complicated task with many agencies involved and a significant amount of money at stake (currently nearly $2 billion per year). Currently, there is no objective mathematical model to support analysts with these complex decisions. Our BASELINE model provides this.

The current practice of equating relative size of the inventory (measured against NNOR Total Munition Requirement) with capability neglects to consider the four component NNOR requirements and the priorities on the variety of potential uses for any munition. The tier level metric provides a munition-specific measure of capability and the minimum tier level achieved by all munitions in a given year provides an objective yardstick for measuring the overall combat effectiveness of the total inventory.

Factors that must be considered by procurement analysts include industrial base constraints, maintenance scheduling, quantity-based pricing, and NNOR component requirements. The Assessment and Investment Model (AIM) is an effective tool for managing all of these considerations and generating multi-year procurement recommendations by placing priority munitions with low tier levels and maximizing the budget available to increase the overall combat effectiveness of the inventory. As increasingly sophisticated weapons, many of which are designed for special purposes, become more common in the inventory, the

ability to optimize any given budget in order to satisfy these complex requirements will be essential.

Together with the AIM spreadsheet interface, this decision support system can provide multi-year munitions procurement plans that will improve the capability of the munition inventory. The Naval Ammunition Logistics Center has provided critical guidance throughout the development of AIM and intends to use AIM for POM planning beginning this fall.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

There are many unexplored opportunities for the continuation of this work. Two have primary significance: improve the fidelity of the model, and improve the responsiveness and quality of the suggested plans.

The actual scheduling, performing, and pricing maintenance on complex munitions is much more complicated than is portrayed in AIM. An initial goal has been to identify maintenance conducted at a Navy facility separately from maintenance done at a contractor facility and represent maintenance costs more accurately, similar to procurement pricing. Ultimately, the data on hand could not support this level of detail, but additional data gathering may support this.

AIM uses GAMS and an off-the-shelf solver, such as CPLEX, for even modestly sized planning problems. Ideally, this tool should be available to procurement analysts, program managers, even commanders in the fleet - none of whom are likely to have access to GAMS or a solver. For practical purposes, a fast heuristic could be used by any

interested party with commonly available software and a more powerful GAMS model could be offered by a central agency (say, NALC) to certify that the heuristic plans are objectively of good quality. We have tried to solve AIM with several basic myopic heuristics. While the plans generated by these heuristics did not result in inventories as capable as those from AIM-generated plans, the heuristics did provide valuable insight into the problem. A more concerted effort at advanced heuristics, perhaps one based on those described by Senju and Toyoda, 1968, and Toyoda, 1975, may be able to produce a tool that can generate solutions comparable to AIM and yet be more accessible to the many interested planners.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. SAMPLE MUNITION DATA

Munition	MSR	MPR	Procurement Delay
AMRAAM	55	388	1
GBU-24 Kit	100	5000	1
GBU-16 Kit	200	18000	1
GBU-12 Kit	200	18000	1
GBU-10 Kit	200	18000	1
Maverick	100	2500	1
Hellfire	200	2700	1
HARM	50	500	1
Sidewinder	100	2056	1
JDAM	1000	12725	1
JSOW (Unitary)	120	600	1
JSOW (Baseline)	300	660	1
MK84	1200	14400	1
MK83	5000	57600	1
MK82	10000	57600	1
Tomahawk 109E	70	504	1
Tomahawk UGM109D	20	504	1
Tomahawk RGM109D	50	104	1
SLAM-ER	30	174	1

Table 9. Munition Production Data

Minimum Sustaining Rate (MSR) and Maximum Production Rate (MPR) are given for munition categories per year. Production Delay is the length of time for procured munitions to arrive in the inventory, in years.

Munition	Maint Cycle Length	Maint Cost	Min Maint Rate	Max Maint Rate	Maintenance Delay
AMRAAM	0	0	0	0	0
GBU-24 Kit	0	0	0	0	0
GBU-16 Kit	0	0	0	0	0
GBU-12 Kit	0	0	0	0	0
GBU-10 Kit	0	0	0	0	0
Maverick	0	0	0	0	0
Hellfire	0	0	0	0	0
HARM	0	0	0	0	0
Sidewinder	5	0.01	100	5886	0
JDAM	0	0	0	0	0
JSOW (Unitary)	0	0	0	0	0
JSOW (Baseline)	0	0	0	0	0
MK84	0	0	0	0	0
MK83	0	0	0	0	0
MK82	0	0	0	0	0
Tomahawk 109E	5	0.3	0	500	0
Tomahawk UGM109D	5	0.3	0	500	0
Tomahawk RGM109D	5	0.3	0	500	0
SLAM-ER	5	0.02	0	350	0

Table 10. Munition Maintenance Data

Cycle Length is the number of years between scheduled maintenance. Maintenance Cost is in M$. Minimum and Maximum Maintenance Rates are in munition counts per year. Maintenance Delay is the time from when a munition begins maintenance until it is again combat useable, in years.

Family 1:	GBU-16 Kit
	GBU-12 Kit
Family 2:	JSOW (Unitary)
	JSOW (Baseline)
Family 3:	Tomahawk 109E
	Tomahawk UGM109D
	Tomahawk RGM109D

Table 11. Designated Munition Families

Munition	Lots 1	2	3	4	5	6	7
AMRAAM							
Lot Count	0	55	120	190	290	388	
Lot Cost	35	28.5	62	85	117	151	
Unit Cost	0.5182	0.9538	1.2143	1.17	1.5408		
GBU-24 Kit							
Lot Count	0	100	1000	3000	5000		
Lot Cost	2	5.5	54	165	270		
Unit Cost	0.055	0.06	0.0825	0.135			
GBU-16 Kit							
Lot Count	0	200	1000	3000	6000	12000	18000
Lot Cost	2	3.4	15	46	92	184	276
Unit Cost	0.017	0.0188	0.023	0.0307	0.0307	0.046	
GBU-12 Kit							
Lot Count	0	200	1000	3000	6000	12000	18000
Lot Cost	2	3.4	15	46	92	184	276
Unit Cost	0.017	0.0188	0.023	0.0307	0.0307	0.046	
GBU-10 Kit							
Lot Count	0	200	1000	3000	6000	12000	18000
Lot Cost	2	4.6	22	64.5	126	240	342
Unit Cost	0.023	0.0275	0.0323	0.042	0.04	0.057	
Maverick							
Lot Count	0	100	600	1200	1800	2500	
Lot Cost	5	16	93	178	265	350	
Unit Cost	0.16	0.186	0.2967	0.4417	0.5		
Hellfire							
Lot Count	0	200	800	1500	2000	2700	
Lot Cost	3	11	45	83	110	140	
Unit Cost	0.055	0.075	0.1186	0.22	0.2		
HARM							
Lot Count	0	50	160	250	400	500	
Lot Cost	15	18	53	75	112	135	
Unit Cost	0.36	0.4818	0.8333	0.7467	1.35		

Table 12. Munition Cost Data I

Lot Count (in munition counts), Lot Cost (in M$), and Unit Cost (in M$ per count) are provided for the first 8 munition categories.

Munition	Lots						
	1	2	3	4	5	6	7
Sidewinder							
Lot Count	0	100	200	450	1000	1500	2050
Lot Cost	25	26	43	83	163	220	290
Unit Cost	0.26	0.43	0.332	0.2964	0.44	0.5273	
JDAM							
Lot Count	0	1000	5000	7000	9000	11000	12725
Lot Cost	15	50	122	161	207	253	285
Unit Cost	0.05	0.0305	0.0805	0.1035	0.1265	0.1652	
JSOW (Unitary)							
Lot Count	0	120	175	300	450	600	
Lot Cost	35	39	57	86	113	156	
Unit Cost	0.325	1.0364	0.688	0.7533	1.04		
JSOW (Baseline)							
Lot Count	0	300	450	660			
Lot Cost	70	85	111	142			
Unit Cost	0.2833	0.74	0.6762				
MK84							
Lot Count	0	1200	4000	10000	14400		
Lot Cost	10	15	50	125	181		
Unit Cost	0.0125	0.0179	0.0208	0.0411			
MK83							
Lot Count	0	5000	20000	40000	57600		
Lot Cost	25	30	120	240	343		
Unit Cost	0.006	0.008	0.012	0.0195			
MK82							
Lot Count	0	10000	16000	34000	57600		
Lot Cost	20	26	42	92	150		
Unit Cost	0.0026	0.007	0.0051	0.0064			
Tomahawk 109E							
Lot Count	0	140	200	325	400	504	
Lot Cost	150	205	252	353	416	494	
Unit Cost	1.4643	4.2	2.824	5.5467	4.75		

Table 13. Munition Cost Data II

Lot Count (in munition counts), Lot Cost (in M$), and Unit Cost (in M$ per count) are provided for the next 8 munition categories.

Munition	Lots						
	1	2	3	4	5	6	7
Tomahawk UGM109D							
Lot Count	0	140	200	325	400	504	
Lot Cost	150	205	252	353	416	494	
Unit Cost	1.4643	4.2	2.824	5.5467	4.75		
Tomahawk RGM109D							
Lot Count	0	140	200	325	400	504	
Lot Cost	150	205	252	353	416	494	
Unit Cost	1.4643	4.2	2.824	5.5467	4.75		
SLAM-ER							
Lot Count	0	30	50	100	140	174	
Lot Cost	30	30	41	63	84	106	
Unit Cost	1	2.05	1.26	2.1	3.1176		

Table 14. Munition Cost Data III

Lot Count (in munitions), Lot Cost (in M$), and Unit Cost (in M$ per count) are provided for the last 3 munition categories.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. AIM MODEL FORMULATION

A. INDICES AND SETS

$m \in M$ Munition, any munition for which NNOR requirements are generated, currently this is 190 possible munitions

$y \in Y$ Year of the planning horizon, $Y=\{1,...,8\}$

$t \in T$ Tier level, $T=\{1,...,\text{num\_tiers}\}$

$l \in L$ Procurement pricing lot, $L=\{1,...,10\}$, there may be up to ten different pricing lots identified for each munition

$f \in F$ Munition facility, $F=\{1,...,f_{max}\}$ where f_{max} is the total number of facilities being modeled

B. DATA

num_lots_m	Number of procurement pricing lots actually used for munition m
$lot\_count_{m,l}$	Number of munition m in lot l
$lot\_cost_{m,l}$	Procurement cost for the full quantity of lot l of munition m
$unit\_cost_{m,l}$	Unit cost per munition m in lot l. Every munition must have at least two lots. For all m, $lot\_count_{m,'1'}=0$, and $lot\_cost_{m,'1'}$ is the penalty charged for violating the minimum sustaining rate for production. Subsequent lot counts and costs represent price reductions due to quantity

	purchasing. Counts and costs are cumulative; use these values as you would a table (interpolating linearly between given values) to determine the total cost for a desired quantity
$mun\_facility_{m,f}$	Value of 1 indicates munition *m* is produced at production facility *f and* maintained at maintenance facility *f′*, 0 required otherwise
$min\_sust\_rate_m$	Minimum production Sustaining Rate (MSR) for munition *m*
$max\_prod\_rate_m$	Maximum Production Rate (MPR) for munition *m*
$prev\_procure_{m,y}$	Number of munition *m* to be delivered in year *y* from previous procurements (before beginning of AIM planning horizon)
$init\_invent_m$	Initial on-hand inventory of munition *m* at the beginning of the planning horizon
$delivery\_delay_m$	Number of years delay for delivery of new procurements of munition *m*
$init\_maint\_due_{m,y}$	Number of munition *m* in the initial inventory due for maintenance in year *y*

$maint\_cycle_m$	Time between scheduled maintenance for munition *m*, if no routine maintenance is required, this value must be large (>8)
$maint\_cost_m$	Unit cost of maintenance for munition *m*
$maint\_delay_m$	Number of years to return a maintained weapon *m* to the active inventory
$max\_maint\_rate_m$	Maximum annual maintenance rate for munition *m*
$min\_maint\_rate_m$	Minimum annual maintenance sustaining rate for munition *m*
$expend\_trng_{m,y}$	Expected annual training expenditures for munition *m* in year *y*
$expend\_ops_{m,y}$	Estimated annual operational expenditures for munition *m* in year *y*
$proc\_budget\_low_y$	Lower bound for annual procurement budget band in year *y*
$proc\_budget\_upp_y$	Upper bound for annual procurement budget band in year *y*
$maint\_budget_y$	Upper bound for annual maintenance budget in year *y*
$disc\_rate$	8-year discount rate for future purchasing dollars from the OMB web site

	(http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html), linearly interpolated between given values
mpr_lot_m	For munition *m*, lot number into which MPR falls
msr_lot_m	For munition *m*, lot number into which MSR falls
mpr_cost_m	Cost for the MPR quantity of munition *m*
msr_cost_m	Cost for the MSR quantity of munition *m*
$max\_prod\_cost_f$	Max annual production output of facility *f*, in total production costs
$min\_sust\_cost_f$	Min annual production output to sustain facility *f*, in total production costs
msr_pen_f	Monetary penalty for violation of facility *f*'s MSR
$mpr\_pen\_rate_f$	Proportional additional penalty cost to facility *f* for exceeding its MPR
$max\_maint\_cost_f$	Max annual maintenance output of facility *f*, in total maintenance costs

$min\_maint\_cost_f$	Min annual output to sustain maintenance facility *f*, in total maintenance costs
excess_maint_rate	Proportional increase in maintenance costs for exceeding the maximum maintenance rate
persist	1 if this is to be solved as a persistent solution
cold2hot	1 to prohibit cold facilities from going hot in a designated number of years
hot2cold	1 to prohibit hot facilities from going cold in a designated number of years
cold2hot_time	Number of years to enforce cold to hot constraint
hot2cold_time	Number of years to enforce hot to cold constraint
change_limit	1 to enforce restrictions on changes in procurement quantities by year
$change\_percent_y$	Limit, as a percentage, to the allowable change in procurements of each munition, from the incumbent solution, in year *y*
$num\_proc_{m,y}$	Number of munition *m* procured in year *y* in the incumbent solution

of_wts_y	Objective function weights, by year y
$holding\_penalty_m$	Objective function penalty for "holding" a munition m in maintenance rather than performing the maintenance
$budget\_penalty_y$	Objective function penalty for underspending the procurement budget lower bound in year y
num_tiers	Number of tier levels in the tier formulation
$tier\_lvl_{m,t,y}$	Number of weapons of type m in year y required to reach tier t

C. VARIABLES

$PROCURED_{m,y}$	Number of munition m procured during year y
$LOT\_PROCURED_{m,l,y}$	Number of munition m procured from lot l in year y
$PROC\_COST_{m,y}$	Total cost of procurement of munition m in year y
$DELIVERED_{m,y}$	Number of munition m delivered during year y from both new procurement and maintenance
$ACTIVE\_INV_{m,y}$	Number of munition m in the usable inventory at the end of year y

$MAINT\_INV_{m,y}$	Number of munition *m* awaiting maintenance (not usable) at the end of year *y*
$MAINT\_DUE_{m,y}$	Number of munition *m* due for maintenance during year *y*
$MAINT\_RTN_{m,y}$	Number of munition *m* returned from maintenance (again usable) during year *y*
$MAINT\_SLACK_{f,y}$	Maintenance throughput of facility *f* below the minimum maintenance sustaining rate in year *y*, in total maintenance costs
$MAINT\_SURPLUS_{f,y}$	Maintenance throughput of facility *f* above the maximum maintenance rate in year *y*, in total maintenance costs
$MIN\_MAINT\_PEN_{f,y}$	Monetary penalty for violation of the minimum maintenance rate for facility *f* in year *y*
$MAX\_MAINT\_PEN_{f,y}$	Monetary penalty for violation of the maximum maintenance rate for facility *f* in year *y*
$OVERPROD_{f,y}$	Value of munitions procured in year *y* from facility *f* above the value of the Max Production Rate
$MPR\_PEN_{f,y}$	Amount of penalty paid for procurements in excess of MPR at facility *f* in year *y*

MIN_TIER_y	Minimum tier achieved of all munitions in year y
$SPEND\_SLACK_y$	Slack variable for spending below the procurement budget lower bound in year y
$PERS\_SLACK_{m,y}$	Slack variable for quantity of munition m by which persistence goals were not met in year y
$COLD\_SLACK_{f,y}$	Slack variable for persistence goals, a 1 indicates a failure to keep facility f "cold" in year y of the updated solution
$HOT\_SLACK_{f,y}$	Slack variable for persistence goals, a 1 indicates a failure to keep facility f "hot" in year y of the updated solution
$CUM\_TIER\_REACHED_{m,t,y}$	Binary variable, 1 if munition m is in tier t or below in year y
$LOT\_INDICATOR_{m,l,y}$	Binary variable, 1 if munition m is being procured in lot l during year y
$MEET\_MSR_{f,y}$	Binary variable, 1 if facility f satisfies its MSR in year y

D. CONSTRAINTS AND OBJECTIVE FUNCTION

MAXIMIZE

$$\sum_{y}\left[\text{of\_wts}_{y}*\left(\text{MIN\_TIER}_{y}-\sum_{f}\left(\text{COLD\_SLACK}_{f,y}+\text{HOT\_SLACK}_{f,y}\right)\right)\right]-\sum_{m,y}\text{PERS\_SLACK}_{m,y}$$
$$+\frac{\sum_{m,y}\left(\text{ACTIVE\_INV}_{m,y}-\text{budget\_penalty}_{y}*\text{SPEND\_SLACK}_{y}-\text{holding\_penalty}_{m}*\text{MAINT\_INV}_{m,y}\right)}{\sum_{m,y}\text{tier\_lvl}_{m,num\_tiers,y}}$$

subject to:

$$\text{ACTIVE\_INV}_{m,y}=\text{init\_invent}_{m}+\text{DELIVERED}_{m,y}-\text{MAINT\_DUE}_{m,y}-\text{expend\_trng}_{m,y}-\text{expend\_ops}_{m,y}\qquad \forall m,\ y=1 \qquad (1)$$

$$\text{ACTIVE\_INV}_{m,y}=\text{ACTIVE\_INV}_{m,y-1}+\text{DELIVERED}_{m,y}-\text{MAINT\_DUE}_{m,y}-\text{expend\_trng}_{m,y}-\text{expend\_ops}_{m,y}\qquad \forall m,y>1 \qquad (2)$$

$$\text{ACTIVE\_INV}_{m,y}\geq\text{tier\_lvl}_{m,'1',y}\qquad \forall m,y \qquad (3)$$

$$\text{DELIVERED}_{m,y}=\text{prev\_procure}_{m,y}+\text{PROCURED}_{m,y'}+\text{MAINT\_RTN}_{m,y''}\qquad \forall m,y \qquad (4)$$
$$\forall y'=y-\text{delivery\_delay}_{m}$$
$$\forall y''=y-\text{maint\_delay}_{m}$$

$$\text{MAINT\_INV}_{m,y}=\text{MAINT\_DUE}_{m,y}-\text{MAINT\_RTN}_{m,y}\qquad \forall m,y=1 \qquad (5)$$

$$\text{MAINT\_INV}_{m,y}=\text{MAINT\_INV}_{m,y-1}+\text{MAINT\_DUE}_{m,y}-\text{MAINT\_RTN}_{m,y}\qquad \forall m,y>1 \qquad (6)$$

$$\text{MAINT\_DUE}_{m,y}=\text{init\_maint\_due}_{m,y}+\text{DELIVERED}_{m,y'}\qquad \forall m,y \qquad (7)$$
$$\forall y'=y-\text{maint\_cycle}_{m}$$

$$\sum_{m}\left(\text{MAINT\_RTN}_{m,y}*\text{maint\_cost}_{m}*\text{mun\_facility}_{m,f}\right)\geq\text{min\_maint\_cost}_{f}-\text{MAINT\_SLACK}_{f,y}\qquad \forall f,y \qquad (8)$$

$$\sum_{m}\left(\text{MAINT\_RTN}_{m,y}*\text{maint\_cost}_{m}*\text{mun\_facility}_{m,f}\right)\leq\text{max\_maint\_cost}_{f}+\text{MAINT\_SURPLUS}_{f,y}\qquad \forall f,y \qquad (9)$$

$$\text{MAX\_MAINT\_PEN}_{f,y}=\text{excess\_maint\_rate}*\text{MAINT\_SURPLUS}_{f,y}\qquad \forall f,y \qquad (10)$$

$$\mathrm{MIN\_MAINT\_PEN}_{f,y} = 1.05 * \mathrm{MAINT\_SLACK}_{f,y} \qquad \forall f,y \qquad (11)$$

$$\sum_{m} \sum_{y'=1}^{y} \left(\mathrm{MAINT\_RTN}_{m,y'} * \mathrm{maint\_cost}_{m} * (1-\mathrm{disc\_rate})^{y'-1} \right) + \sum_{f} \sum_{y'=1}^{y} \left(\begin{array}{l} \mathrm{MAX\_MAINT\_PEN}_{f,y'} + \\ \mathrm{MIN\_MAINT\_PEN}_{f,y'} * (1-\mathrm{disc\_rate})^{y'-1} \end{array} \right) \leq \sum_{y'=1}^{y} \mathrm{maint\_budget\_upp}_{y'} \qquad \forall m,y \qquad (12)$$

$$\mathrm{PROCURED}_{m,y} = \sum_{l=1}^{\mathrm{num\_lots}_{m}} \mathrm{LOT\_PROCURED}_{m,l,y} \qquad \forall m,l,y \qquad (13)$$

$$\mathrm{LOT\_PROCURED}_{m,l,y} \geq \left(\mathrm{lot\_count}_{m,l+1} - \mathrm{lot\_count}_{m,l} \right) * \mathrm{LOT\_INDICATOR}_{m,l+1,y} \qquad \forall m,y,\ l<\mathrm{num\_lots}_{m} \qquad (14)$$

$$\mathrm{LOT\_PROCURED}_{m,l,y} \leq \left(\mathrm{lot\_count}_{m,l+1} - \mathrm{lot\_count}_{m,l} \right) * \mathrm{LOT\_INDICATOR}_{m,l,y} \qquad \forall m,y,\ l<\mathrm{num\_lots}_{m} \qquad (15)$$

$$\mathrm{LOT\_PROCURED}_{m,l,y} \leq \left(\mathrm{tier\_lvl}_{m,num\_tiers,y} - \mathrm{lot\_count}_{m,l} \right) * \mathrm{LOT\_INDICATOR}_{m,l,y} \qquad \forall m,y,\ l=\mathrm{num\_lots}_{m} \qquad (16)$$

$$\sum_{m} \left(\mathrm{PROC\_COST}_{m,y} * \mathrm{mun\_facility}_{m,f} \right) \leq \mathrm{max\_prod\_cost}_{f} + \mathrm{OVERPROD}_{f,y} \qquad \forall f,y \qquad (17)$$

$$\sum_{m} \left(\mathrm{PROC\_COST}_{m,y} * \mathrm{mun\_facility}_{m,f} \right) \geq \mathrm{MEET\_MSR}_{f,y} * \mathrm{min\_sust\_cost}_{f} \qquad \forall f,y \qquad (18)$$

$$\sum_{m} \left(\mathrm{PROC\_COST}_{m,y} * \mathrm{mun\_facility}_{m,f} \right) \leq \mathrm{MEET\_MSR}_{f,y} * \sum_{m} \left(\mathrm{mun\_facility}_{m,f} * \mathrm{tier\_lvl}_{m,num\_tiers,y} \right) \qquad \forall f,y \qquad (19)$$

$$\mathrm{MPR\_PEN}_{f,y} = \mathrm{mpr\_pen\_rate}_{f} * \mathrm{OVERPROD}_{f,y} \qquad \forall f,y \qquad (20)$$

$$\text{PROC\_COST}_{m,y} = \sum_{l=1}^{num\_lots_m} \left(\text{LOT\_PROCURED}_{m,l,y} * \text{unit\_cost}_{m,l}\right) \qquad \forall m,y \qquad (21)$$

$$\begin{aligned}&\sum_{m}\sum_{y'=1}^{y}\left(\text{PROC\_COST}_{m,y'} * (1-\text{disc\_rate})^{y'-1}\right) + \\ &\quad \sum_{f}\sum_{y'=1}^{y}\left[\left(\text{MPR\_PEN}_{f,y'} + \left(1-\text{MEET\_MSR}_{f,y'}\right) * \text{msr\_pen}_f\right) * (1-\text{disc\_rate})^{y'-1}\right] \\ &\quad \le \sum_{y'=1}^{y} \text{proc\_budget\_upp}_{y'}\end{aligned} \qquad \forall y \qquad (22)$$

$$\begin{aligned}&\sum_{y'=1}^{y}\left[\left(\text{SPEND\_SLACK}_{y'} + \sum_{m}\text{PROC\_COST}_{m,y'}\right) * (1-\text{disc\_rate})^{y'-1}\right] + \\ &\quad \sum_{f}\sum_{y'=1}^{y}\left[\left(\text{MPR\_PEN}_{f,y'} + \left(1-\text{MEET\_MSR}_{f,y'}\right) * \text{msr\_pen}_f\right) * (1-\text{disc\_rate})^{y'-1}\right] \\ &\quad \ge \sum_{y'=1}^{y} \text{proc\_budget\_low}_{y'}\end{aligned} \qquad \forall y \qquad (23)$$

$$\begin{aligned}&\text{ACTIVE\_INV}_{m,y} \ge \text{tier\_lvl}_{m,'1',y} * \\ &\quad \text{CUM\_TIER\_REACHED}_{m,'1',y} + \\ &\quad \sum_{t=2}^{num\_tiers}\left[\text{tier\_lvl}_{m,t,y} * \left(\text{CUM\_TIER\_REACHED}_{m,t,y} - \text{CUM\_TIER\_REACHED}_{m,t-1,y}\right)\right]\end{aligned} \qquad \forall m,y \qquad (24)$$

$$\begin{aligned}&\text{ACTIVE\_INV}_{m,y} \le \text{tier\_lvl}_{m,num\_tiers,y} * \\ &\quad \left(\text{CUM\_TIER\_REACHED}_{m,num\_tiers,y} - \text{CUM\_TIER\_REACHED}_{m,num\_tiers-1,y}\right) + \\ &\quad \sum_{t=1}^{num\_tiers-1}\left[\left(\text{tier\_lvl}_{m,t+1,y} - 1\right) * \left(\text{CUM\_TIER\_REACHED}_{m,t,y} - \text{CUM\_TIER\_REACHED}_{m,t-1,y}\right)\right]\end{aligned} \qquad \forall m,y \qquad (25)$$

$$\text{CUM\_TIER\_REACHED}_{m,t+1,y} \ge \text{CUM\_TIER\_REACHED}_{m,t,y} \qquad \forall m,y,\ t<num\_tiers \qquad (26)$$

$$\text{MIN\_TIER}_y \le \sum_{t=2}^{num\_tiers} \begin{pmatrix} t*\text{CUM\_TIER\_REACHED}_{m,t,y} \\ -\text{CUM\_TIER\_REACHED}_{m,t-1,y} \end{pmatrix} + \text{CUM\_TIER\_REACHED}_{m,'1',y} \quad \forall m,y \qquad (27)$$

Persistence constraints:
If persist=1 and change_limit=1 and change_percent$_y$>0,

$$\text{PROCURED}_{m,y}/\text{num\_proc}_{m,y} \ge 1\text{-change\_percent}_y\text{-PERS\_SLACK}_{m,y} \quad \forall m,y \qquad (28)$$

If persist=1 and change_limit=1 and change_percent$_y$>0,

$$\text{PROCURED}_{m,y}/\text{num\_proc}_{m,y} \le 1\text{+change\_percent}_y\text{+PERS\_SLACK}_{m,y} \quad \forall m,y \qquad (29)$$

If persist=1 and cold2hot=1 and cold2hot_time>y,

$$\text{MEET\_MSR}_{f,y} \le \sum_m \left(\text{num\_proc}_{m,y}*\text{mun\_facility}_{m,f}\right)+\text{COLD\_SLACK}_{f,y} \quad \forall f,y \qquad (30)$$

If persist=1 and hot2cold=1 and hot2cold_time>y,

$$\text{MEET\_MSR}_{f,y} \ge \frac{\sum_m \left(\text{num\_proc}_{m,y}*\text{mun\_facility}_{m,f}\right)}{\sum_m \left(\text{num\_proc}_{m,y}*\text{mun\_facility}_{m,f}\right)+1} \text{-HOT\_SLACK}_{f,y} \quad \forall f,y \qquad (31)$$

$$\begin{aligned} &\text{PROCURED}_{m,y},\ \text{LOT\_PROCURED}_{m,l,y},\ \text{PROC\_COST}_{m,y},\ \text{DELIVERED}_{m,y}, \\ &\text{ACTIVE\_INV}_{m,y},\ \text{MAINT\_INV}_{m,y},\ \text{MAINT\_DUE}_{m,y},\ \text{MAINT\_RTN}_{m,y}, \\ &\text{MAINT\_SLACK}_{f,y},\ \text{MAINT\_SURPLUS}_{f,y},\ \text{MIN\_MAINT\_PEN}_{f,y}, \\ &\text{MAX\_MAINT\_PEN}_{f,y},\ \text{OVERPROD}_{f,y},\ \text{MPR\_PEN}_{f,y},\ \text{MIN\_TIER}_y, \\ &\text{SPEND\_SLACK}_y,\ \text{PERS\_SLACK}_y, \\ &\text{COLD\_SLACK}_y,\ \text{HOT\_SLACK}_y \ge 0 \quad \forall m,y,t,l \qquad (32) \end{aligned}$$

$$\begin{aligned} &\text{CUM\_TIER\_REACHED}_{m,t,y},\ \text{LOT\_INDICATOR}_{m,l,y}, \\ &\text{MEET\_MSR}_{f,y} \text{ are Binary} \quad \forall m,y,t,l \qquad (33) \end{aligned}$$

E. BRIEF VERBAL DESCRIPTION

The objective function expresses the weighted sum of the annual minimum tier achieved, less penalties for violations of persistence, plus the sum of annual inventories as a proportion of the total desired inventory,

less penalties for underspending on procurement and delaying maintenance.

Constraints:

(1-2) Together, these are inventory balance equations for each active (combat useable) munition.

(3) Each constraint requires that the minimum active inventory of a munition be maintained every year.

(4) Each constraint determines the number of a newly produced or maintained munition that is delivered in a given year.

(5-6) Together, these are inventory balance equations for a unusable munition that is waiting for maintenance.

(7) Maintenance scheduling equations; these determine the number of a munition that are due for maintenance in a given year.

(8-9) These elastic constraints enforce the maintenance base for the minimum and maximum maintenance throughput, in cost, in a given year for a given facility. A violation ($MAINT\_SLACK_{f,y}$ and $MAINT\_SURPLUS_{f,y}$) results in an increased maintenance cost.

(10-11) These equations determine the penalties for a violation of a maintenance base constraint.

(12) Each constraint limits cumulative maintenance spending (including penalties) by the cumulative maintenance budget.

(13) This equation determines the total number of a munition procured in a given year by summing procurements over all individual lots.

(14-16) Together, these constraints require that an individual lot procurement is no larger in count than the count of the entire lot (or the NNOR total requirement when purchasing from the last lot) and that a munition may not be procured from the next lot without procuring the entire previous lot.

(17) Each elastic constraint restricts procurement production at a facility by the maximum production rate (MPR). A violation ($OVERPROD_{f,y}$) results in a penalty which increases procurement cost.

(18-19) Together, these constraints determine whether the minimum sustaining production rate (MSR) for a facility has been met. A failure to meet the MSR results in a penalty on overall procurement spending.

(20) Each equation determines the penalty for a violation of a facility's MPR.

(21) Each equation determines the total cost of new procurement of a single munition in a given year.

(22-23) Together these constraints enforce the upper and lower bounds on cumulative procurement budget spending, discounted for future years and including penalties.

(24-25) Together, these constraints determine which tier has been reached based on a current (active) inventory count.

(26) These constraints require the tier reached indicator variable to be non-decreasing.

(27) Each constraint determines the minimum tier achieved in a given year.

(28-29) These constraints are active only when a persistent recommendation is desired. Together they require the quantity of a munition procured in a given year to be within a relative range of the quantity from the original recommendation.

(30-31) These elastic constraints require that a facility does not change status in the revised plan from “cold” to “hot” or “hot” to “cold” for a designated number of years. A violation ($COLD\_SLACK_{f,y}$ and $HOT\text{-}SLACK_{f,y}$) is penalized in the objective function.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. AIM USER'S GUIDE

The following are the general steps required to prepare the necessary data to solve a munition procurement problem with AIM.

Step 1: Generate tier level tables.

The percentages that apply to specific NNOR requirements can be adjusted to any series of non-decreasing levels (from Level F, the poorest, to Level A, the best) if necessary to better focus on the range of current munition inventories. Similarly, the progression up through these mission capability levels may be changed from the current structure shown in this paper. Fewer than sixteen tier levels may be used, but not more than sixteen (i.e., this is an implementation limit). Tier 1 should represent the smallest acceptable munition inventory; the highest tier used should equal the NNOR TMR.

Setting the mission area priorities for each munition can be done with input from the agencies involved in munition procurement planning and inventory management as well as from the program manager responsible for that munition. The key question to be answered in determining these priorities is, "If supply of this munition is limited, for which mission area is it most critical that this munition be available in its desired quantity?"

Following calculation of the tier level values for each tier by munition and year, these values should be

listed in table format in a comma-delimited text file named "tierLevels.txt". The format is as follows:

Line 1: dummy, dummy, 1,2,3,4,5,6,7,8

Subsequent lines: munition name, tier number, tier level values for each of the eight years

Step 2: Assign munition families.

The AIM formulation recognizes munition-family assignments by the "mun_facility" variable indexed by munition and facility. A "1" indicates the munition is a member of the family produced at this facility, a "0" is necessary otherwise.

The values of the "mun_facility" variable should be contained in a comma-delimited text file in table format named "FacilityTable.txt". The format includes the facility designators, as column headings (led by a single dummy placeholder), in the first line, and the munition names as rows followed by a "0" or "1" as indicated above for each facility.

Two text files indicating the set of munitions and the set of facilities can be prepared at this time. The former, titled "munitionSet.txt", should lead with a single forward slash ("/"), then each munition name followed by a comma should be listed on a separate line (the last munition should not be followed by a comma). The last line of the file should consist of simply a single forward slash ("/"). The file containing the set of facilities should be named "facilitySet.txt" and have a similar format.

Step 3: Prepare munition data.

All industrial base and maintenance throughput constraints are given in number of munitions. These values should refer to constraints on individual munitions production and maintenance; the individual constraints will be converted into family constraints within AIM. Time quantities are always in units of years. Of note are the three types of maintenance requirement:

1. No regular maintenance required. For these munitions, the value given for length of the maintenance cycle should be large (>8).

2. Regular maintenance required. For these munitions, the length of the maintenance cycle represents the number of years between regularly scheduled maintenance. The maintenance cost is given in M$ per munition maintained.

3. Limited lifespan. Some munitions require no regular maintenance, but there is some time limit to their useful life. For these munitions, the maintenance cycle length should be set to the given lifespan and the maintenance cost should be very large (perhaps 999 M$) to preclude any effort at maintenance of these munitions.

Munition data is provided to AIM in three text files. The first file, titled "MunitionData.txt" contains individual munition data that is constant over all years. This file requires no leading or trailing lines, and for each munition, the following format should be used:

Init_invent('*munition name*')= *value* ;
Maint_cycle('*munition name*')= *value* ;

```
Maint_cost('munition name')= value ;
Min_sust_rate('munition name')= value ;
Max_prod_rate('munition name')= value ;
Min_maint_rate('munition name')= value ;
Max_maint_rate('munition name')= value ;
delivery_delay('munition name')= value ;
Maint_delay('munition name')= value ;
num_lots('munition name')= value ;
```

The second file contains munition data that varies by year. It is a comma-delimited file in table format and should be named "MunitionTable1.txt". The lead line consists of two dummy placeholders and then the values 1 through 8 (years). Each munition will be represented in four rows. The first two elements in each row will be the munition name and a numeral 1 through 5. The rows numbered 1 will indicate annual maintenance requirements for the munitions in the current (beginning) inventory. The rows numbered 2 will show the number of previously procured munitions that will arrive in each year. The rows numbered 3 and 4 provide annual expected training and operational expenditures, respectively. The rows numbered 5 provide the original solution (in values of the quantity of this munition procured in each year) when the model will be solved to include persistence constraints.

The third file is also a comma-delimited file in table format and should be named "MunitionTable2.txt". This file contains the procurement cost data. The lead line consists of two dummy placeholders and then the values 1 through 10 (lots). Each munition will be represented in two rows. The first two elements in each row will be the munition

name and a numeral 1 or 2. The rows numbered 1 will indicate lot size (quantities of munitions) for increasingly larger lots. The rows numbered 2 will provide lot costs for each lot. An important note is that while most munitions will probably be represented in fewer than ten lots, there must be a total of eleven delimiters to represent all twelve columns (two for munition and row indicator, ten for lots).

Step 4: Set global variables.

Determine minimum and maximum procurement budget values, by year, and allowable maintenance budget, by year. Due to fixed cost penalties for violations of Minimum Sustaining Rate, there is a minimum budget allowance that is necessary to guarantee feasibility. The cumulate accounting of procurement spending provides some flexibility, but the sum of the MSR penalties over all facilities determines the minimum annual procurement budget.

Step 5: If desired, set persistence parameters and provide a legacy plan.

Persistence requirements can be imposed in two general areas: individual munition annual procurement, and change to the industrial base. In order to apply persistence constraints, the number of each munition procured, by year, in the legacy plan is provided as a parameter to AIM.

The global parameters and persistence options will be contained in a final comma-delimited text file in table format. The lead line consists of one dummy placeholder and then the values 1 through 8 (years). Following are five lines; they begin with the values 1 through 3, 5, and 6 (4 is currently unused). The rows numbered 1 and 2 provide the minimum and maximum procurement budget, respectively, for each year. The row numbered 3 provides the allowable maintenance budget for each year.

The row numbered 5 indicates a different, single quantity in each of the columns (for this row the columns do not correspond to years). With the number 5 in the first position, the second position holds the discount rate to be used (as a quantity from 0.0 to 1.00). The third position holds the overall persistence indicator, a "1" to allow persistence constraints, a "0" otherwise. The fourth, fifth, and sixth positions contain the indicators for the constraints on industrial base and procurement quantity changes. A "1" in the fourth position activates the constraint preventing inactive facilities from becoming active. A "1" in the fifth position activates the constraint preventing active facilities from becoming inactive. A "1" in the sixth position activates the constraint limiting the allowed relative change to individual munition procurement quantities. Note that in order for any of these three individual persistence options to be activated, the overall persistence indicator (in position three) must also be set to "1". The seventh and eighth positions provide the length of time (in number of years) for the change in industrial base constraints to be in effect (provided they are activated as described above).

Finally, the ninth position should indicate the number of tiers used in the chosen tier structure.

The row numbered six contains the fraction of change allowed, by year, to individual munition procurements, when this constraint is activated.

The steps above will generate eight text files required by AIM. Upon successfully solving a problem, the basic results (to include quantity of munitions procured and quantity of munitions maintained, by munition and year, and total procurement spending and total maintenance spending, by year) are reported in a comma-delimited text file under the name designated by the user in the GAMS program.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Brook, A., Kendrick, D., Meeraus, A., Raman, R. [1998] GAMS: A User's Guide. Washington DC: The Scientific Press.

Brown, Gerald G., Dell, Robert F. and Wood, R. Kevin, [1997] "Optimization and Persistence", INTERFACES, September/October, Vol. 27, Number 5.

Chief of Naval Operations Instruction 8011.9A (OPNAVINST 8011.9A): Non-Nuclear Ordnance Requirements (NNOR) Process [1989].

Department of the Navy Report [2003]. Highlights of the 2004 President's Budget, Appendix A – Supporting Tables. Accessed 15 August 2003 via the World Wide Web at http://navweb.secnav.navy.mil/pubbud/04pres/highbook/Appendix_A.pdf.

Department of Defense Instruction 3000.4: Capabilities-Based Munitions Requirements (CBMR) Process [2001].

Fahringer, Phil, CDR, [2002] USN, Naval Supply Systems Command – Naval Ammunition Logistics Center, various interviews 13-27 November.

ILOG CPLEX. Product documentation, accessed 23 September 2003 via http://www.ilog.com/products/cplex/.

Naval Ammunition Logistics Center (NALC) [2003], AIM input files acquired 18 August.

Office of Management and Budget [2003]. Circular Number A-94, Appendix C – Discount Rates for Cost Effectiveness, Lease Purchase, and Related Analysis. Accessed 3 June 2003 via the World Wide Web at http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html.

Page, Alfred N. (ed) [1968] Utility Theory: A Book of Readings. New York: John Wiley and Sons, Inc.

Senju, Shizuo and Toyoda, Yoshiaki [1968] "An Approach to Linear Programming with 0-1 Variables", Management Science, Volume 15, Number 4, pp. B-196 – B-207.

Toyoda, Yoshiaki [1975] "A Simplified Algorithm for Obtaining Approximate Solutions to Zero-One Programming Problems", Management Science, Volume 21, Number 12, pp. 1417 - 1427.

United States General Accounting Office Report to the Ranking Minority Member, Subcommittee on Readiness and Management Support, Committee on Armed Services, U.S. Senate [July 2001]. MILITARY READINESS: Management of Naval Aviation Training Munitions Can Be Improved.

Wikipedia online encyclopedia [2003]. "'Utility' in Economics and Game Theory", accessed 29 August 2003 via http://www.wikipedia.org/wiki/Utility.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Marine Corps Representative
   Naval Postgraduate School
   Monterey, CA

4. Director, Training and Education, MCCDC, Code C46
   Quantico, VA

5. Director, Marine Corps Research Center, MCCDC, Code C40RC
   Quantico, VA

6. Marine Corps Tactical Systems Support Activity, (Attn: Operations Officer)
   Camp Pendleton, CA

7. Director, Studies and Analysis Division, MCCDC, Code C45
   Quantico, VA

8. CDR Phil Gonda
   Naval Ammunition Logistics Center, NALC 09A9
   Mechanicsburg, PA

9. Professor W. Matthew Carlyle (Code OR)
   Naval Postgraduate School
   Monterey, CA

10. Professor Gerald G. Brown (Code OR)
    Naval Postgraduate School
    Monterey, CA